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LONG RANGE ELECTRO-OPTICAL RECONNAISSANCE SYSTEM (U)

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Fairchild Weston Systems Inc.
Syosset, New York 11791

May 1982

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(U) THIS REPORT DESCRIBES THE EVOLUTION OF ELECTRO-OPTICAL TECHNIQUES REQUIRED TO EXTRACT USEFUL IMAGERY FROM HAZE-OCCLUDED LOW OBJECT CONTRAST SCENERY. THE PROBLEM OF GENERATING SUFFICIENT SIGNAL ELECTRONS (AND CORRESPONDING SIGNAL-TO-NOISE RATIOS) SO AS TO ENABLE D.C. BACKGROUND HAZE SUBTRACTION AND AMPLIFICATION OF USEFUL A.C. INTER-PIXEL SIGNAL COMPONENTS IS STATED. THE CCD-TDI PHOTOSENSOR WITH A 'TAP' SELECTABLE NUMBER OF INTEGRATIONS IS PRESENTED AS A VIABLE SOLUTION TO THE PROBLEM OF NOISE LIMITED IMAGE ENHANCEMENT OF LONG RANGE TARGETS IN WHICH THE OBJECT CONTRAST LEVEL

IS BOTH VISUALLY AND PHOTOGRAPHICALLY UNDETECTABLE.

(U) A GENERAL DISCUSSION OF LOREORS SIGNAL PROCESSING IS PRESENTED, INCLUDING "UNSHARP MASKING" TO ENHANCE HIGH SPATIAL FREQUENCY A.C. SIGNAL COMPONENTS. THIS SHARPENS THE SCENE DETAIL BY EMPHASIZING SIGNAL LEVEL CHANGES. "UNSHARP MASKING", OR LOW SPATIAL FREQUENCY FILTERING, ALSO EXTENDS USABLE SIGNAL DYNAMIC RANGE BY REMOVING A D.C. BIAS IN THE HIGHLY ILLUMINATED IMAGERY WHICH CAUSES HIGH AMPLITUDE SIGNALS TO SATURATE SOONER THAN THE LOW AMPLITUDE LEVELS. THIS ENABLES FURTHER AMPLIFICATION OF IN SCENE DETAIL ACROSS THE DYNAMIC RANGE EXTREMES.

(U) A SUMMARY OF LOREORS TECHNOLOGY, FOLLOWED BY A CHRONOLOGY OF LOREORS PROGRAM EVOLUTION, CULMINATING IN SYSTEM DEVELOPMENT, FABRICATION, AND FLIGHT TESTING IS PRESENTED.

(U) THE FINAL SECTION OF THIS REPORT DELINEATES THE MAJOR SYSTEM AND SUBSYSTEM COMPONENTS COMPRISING THE LOREORS UNIT AND DESCRIBES THEIR OPERATING PRINCIPLES.

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(U) 1.0 INTRODUCTION

(U) Fairchild Imaging Systems, Division of Fairchild Weston Systems Inc., has completed contract F33615-76-C-1282 for the Avionics Laboratory. The primary goal was to demonstrate optical penetration of haze-occluded low contrast scenery with an imaging system configured about an array of Time Delay and Integration (TDI) - Charge Coupled Devices (CCD).

(U) With an electro-optical imager, it is possible to electronically subtract the background due to haze from each picture element (PIXEL) and amplify the remaining pixel-to-pixel differences to enhance the reproduced scene. In principle, such processing can be carried to contrast levels which would be both invisible to the eye and unrecordable by conventional photography.

(U) For this to be practical, a large image signal-to-noise ratio is required. One way to collect the large signal needed is through the use of a TDI imager. Such a TDI CCD detector with a selectable number of integrations was developed and furnished to the program.

(C) This chip consisted of rows of 20 micrometer photo elements; 1024 pixels wide arranged in columns 64 pixels high. The number of TDI integrations (1, 4, 8, 16, 32 or 64) could be selected. The saturation charge was in excess of 1.0×10^6 electrons per pixel in this four-phase buried channel device.

(C) An optically-butted focal plane was made using 6 of these chips mounted on a beam-sharer having alternate full-reflective and fully-transparent segments. The focal plane was joined with a 3.66m (144") focal length f/12 refractive telephoto lens which provided essentially diffraction-limited performance throughout the silicon spectrum over a 6° field of view.

(U) The sensor was of the sector-scan panoramic type, designed to be mounted with its axis parallel to the in-track (flight) direction. Cross-track scan coverage was obtained by rotating a 45° folding mirror, directed (nominally) at right angles to the line of flight, about the in-track axis. Forward Motion Compensation (FMC) and image stabilization were obtained through computer-controlled scan mirror pointing corrections and focal plane rotations. Line-of-sight, pointing and scan control inter-active commands were generated in the computer using inputs from the airborne inertial navigational system. Pointing and scan rates of up to 1°/second were generated by the computer based upon manually input target latitude and longitude values and aircraft inertial navigation system data.

An Environmental Control Subsystem was comprised of Isolation Mounts to filter out shock and vibration, a Temperature Control of the sensor and a Thermoelectric Cooler to further cool the CCD focal plane. The Temperature Control subsystem provided both heating and cooling to maintain the total sensor temperature within 1°.

A real-time autocollimator type of Auto-focus subsystem measured and automatically set the "infinity focus" of the objective, thus providing optimum focus throughout a broad range of temperatures and pressures. Range focus differentials were controlled by the computer using data from the target deck and aircraft systems.

The Airborne Video Subsystem consisted of the CCD focal plane, exposure sensing diodes and IMC circuitry. Eight CCD chips were used in the focal plane; 6 devices to convert the optical image to an analog video signal and 2 devices to detect IMC errors and supply an error signal to the computer. This focal plane could be expanded to contain 18 or more CCD chips.

Array drivers and logic (controlled by an end-of-line sync signal), a 1.45 clock and an "integration duration" signal from the Video Processor, supplied timing and control signals to process the image signal through the CCD detectors and develop the serial video output signal transmitted to the Processor Console.

Fifteen exposure-control diodes placed within the "frame" field of view develop an automatic exposure signal transmitted to the computer to set the number of TDI integrations required.

small inaccurate trigonometric functions. Pointing and stabilization were found to be affected by the relatively infrequent Latitude and Longitude updating every(500/m-sec) while computation is performed every 20 m-sec. The uncertainties in the aircraft altitude and accuracy of the line of site (due to atmospheric refraction) were also investigated and found to be potential sources of excessive error.

2.2.4.2 Fabrication

At the completion of the sensor design around midyear of 1978 the fabrication effort was in full progress. Except for the optical component Melt Recomputation the fabrication effort was fairly routine. As the assembly and electrical fabrication progressed through the second half of '78, subassembly testing was conducted. Quarterly Program review meetings were held and the pacing items were the optical components; specifically the lens.

2.2.4.3 System Tests

By the beginning of 1979 the Ground Station equipment was completed and fully tested. System tests on the sensor were started during the first quarter of 1979. With the system installed on the Photo Optical Terrain Simulator a problem was found while trying to measure resolution.

Initial resolution and autofocus tests indicated a discrepancy of one half of one percent between the actual and design focus point of the system. Mechanical tolerance analysis and optical analysis could only justify one quarter of an inch.

It was found that a lens barrel "bend", between the Objective and Barlow groups, of 35 microradians combined with as much as a 0.001 inch displacement would not degrade optical performance. Modeling showed that the total bending of the barrel statically and dynamically would be less than 35 microradians.

- Analysis of aircraft window thermal shock caused by rapid descent from altitude was performed. Also methods for maintaining an isothermal condition across the window interior was investigated. It was found that maximum stress was developed near the center of the window. Based on initial results a safe descent time of one hour was recommended. Increased air flow would reduce this. Further analysis of the window thermal environment are discussed in Appendix B.

(U) Computer simulations, performed to analyze proposed processes and access their feasibility involved;

- The image processing algorithm, where the enhancement procedures were simulated. Unsharp averaging, Sharp-minus-Unsharp generation, data compression and data reconstruction were programmed on the computer. Several algorithm variations were tried and the results compared to determine the best enhancement approach for the system.
- CCD chip calibration processes were programmed to simulate the actual device and computer interfacing required.
- Equations of motion for the scan and FMC angles and the focal plane rotation were programmed. First results indicated that the pointing accuracy and stabilization would be limited by the difficulties of working with very

- Array Signature Correction
- Video Amplification
- Unsharp and Sharp-Minus-Unsharp Video
- Analog-to-digital conversion circuitry
- Max-Min Detection with gain and offset normalization
- Array Timing Logic and Driver Circuitry
- Preliminary 1024 x 64 TDI-CCD Signal Processing
- Forward Motion Compensation Signal Processing
- Automatic Exposure Control Circuit.

(U) Additional design studies resulted in the development of altered design approaches and solutions. Among these were:

- The Focal Plane Cooling design was revised to permit replacement of thermoelectric coolers without breaking the hemetic seal of the focal plane compartment. Large surface-area heat dissipators, located in the external environmental air stream, draw the heat from the fixed internal thermo-electric heaters thus minimizing the focal plane housing heat rise. Analyses revealed that a second stage of thermoelectric cooling was required. A two-stage thermoelectric device was therefore used.
- Forward Motion Compensation signal processing was changed from an analog system using Hilbert Transform filtering to a double correlator one. An all-digital subsystem using TRW 400 nanosecond multipliers was designed to attain the accuracy and long-term DC stability required.
- An investigation of the Tolerance sensitivity of specific lens element configurations was made. It was determined that three pairs of elements were most critical. Carefully assembling and treating of each such doublet as a "single element" enabled maintenance of the memory tolerances.

- Fabrication of the calibration light source and temperature control units were delayed so these units could be interfaced with the new computer.
- The number of operating sensor channels were reduced from 18 to 6. All associated circuitry was comensurately modified.
- The requirement for the Laser Beam Recorder and the Dry Silver Processor was reinstated.

(U) 2.2.4 LOREORS Development

(U) Following the CDR approval, system design and detailing for the hardware was initiated. Using computer simulation and breadboard modeling, proposed design concepts were tested to determine design parameters and to "test" components in the proposed configurations.

[redacted] During this period a parallel company-sponsored IR&D program was funded to tailor a Fairchild TDI-CCD chip for LOREORS imaging. A 1024 x 64 element TDI device was developed for low signal applications. This image detector was designed with the minimum cell size capable of producing the high signal-to-noise required; a 60db goal was set near saturation with a charge packet level of at least 10^6 electrons. A four-phase CCD configuration, with 20 x 20 μm photosensitive elements in a parallel register, was developed. The active length of this chip is 20.48 mm (0.806"). A more complete description is given in the R. Dyck paper included in Appendix A.

(U) 2.2.4.1 Sensor Design

(U) Major subsystem circuits and processes were "tried out" in a pre-fabrication form in order to minimize final system changes. Some of the processes and component breadboards were:

(U) Additional changes requested at that time were:

- Changing the image storage Video Tape Recorder Unit (VTR) from an Analog to a Digital Unit.
- Elimination of the Laser Beam Recorder (LBR) and hence the Dry Silver Processor requirements although interface provisions for future use of these items were requested.
- An investigation of the feasibility of using a single frame storage scan converter with a high resolution CRT Display for a soft copy output.
- An initial design of a 144" focal length lens to meet the system resolution requirements in place of a 96" focal length with a future add-on.

(U) During the first nine months of this program the final definition of the system was developed. Additionally an "In-House" development program was in progress for the LOREORS, TDI-CCD chip at Fairchild's Palo Alto, R&D Laboratory. A search was also conducted for critical system components sources.

(U) 2.2.3 Critical Design Review

(U) The Critical Design Review was held at Fairchild on September 20 through 23, 1977. Detailing of subassemblies and parts was started and parts procurement was intitated. Air Force approval of the CDR was received one month later on October 20th. As a result of the CDR the following changes were incorporated in the system.

- An INS was being incorporated into the system. A GFE system was supplied.
- A system clock was added.
- A Data Logger was added; additional computer capacity and a printer were added to permit recording of instrumentation data.
- A Hewlett Packard computer replaced a previously specified Data General Unit.

(U) The system was to be designed for either digital telemetry direct from aircraft to ground station and/or airborne video tape recording for later playback in the ground station. For this program, an RCA Adviser Series VTR was proposed.

(U) The ground station consisted of an electronic buffer, laser beam recorder, dry silver processor and light table installed in a trailer. Fairchild proposed to modify a GFE'd LBR and convert the wet film processor to accommodate dry silver film.

(U) 2.2.2 Program Initiation

(U) Contract award was made in January 1977. Although the basic system concept for LOREORS was accepted as proposed, some changes were agreed upon at the kickoff meetings.

(U) FISD personnel presented a description of the sensor geometry and detailed the stabilization approach proposed. It was indicated that two areas of concern were the respective loop stabilization methods and the means for generating stability reference signals. The concern was over the ability to maintain an adequate lock on the image throughout a long exposure with a full sixty-four integrations. It was suggested that the system utilize dynamic stabilization (i.e.; with computer updating) rather than the passive type of system proposed.

(U) It was also specified that the system test vehicle would be a C-141 with flight tests to be at 40,000 and 10,000 feet. The C141 has an inertial reference system which could be used for sensor stabilization; the Delco, Carousel 4E (INS) Inertial Navigational System. This system has a 0.7 nautical-mile/hour, typical error specification but has been found to actually track to better than 0.2 nm/hr.

(U) The proposed sensor assembly rotated radially to achieve cross-track positioning. A scanning mirror moved in the cross-track direction of flight to generate a "frame" of information. A linear array of CCD photosensors was positioned along the longitudinal axis of the aircraft. The sensor could be manually controlled by a commander who would use a low resolution TV image of the object area for targeting assistance. This display indicated the high resolution camera's line-of-sight. Provisions were made in the design to implement a computer directed targeting system in the future. The low resolution TV "viewfinder" camera would utilize a 488 x 380 CCD device permitting frame storage for contrast enhancement.

(U) The proposed sensor employed autofocus, stabilization, motion compensation and position and environmental control. The focal plane consisted of 18 Fairchild CCD#ISD 131-SL die assembled on a beam-sharer to form a contiguous line. The beam-sharer was 98% optically efficient. The die (photo-sensor without package) were standard Fairchild 1 x 1024 elements sensors with selected performance. The characteristics to be used in the selection process were dynamic range, large saturation exposure, low noise equivalent exposure, low dark current, uniformity of dark current and high sensitivity. These die, considered non-standard because of the selection process, were available only to FISD. The focal plane was to be assembled in FISD's Hybrid Laboratory.

(U) Both the TV "viewfinder" and high resolution electro-optical imager were to use analog image processing to enhance contrast. Background subtraction and non-sharp masking, were to be employed. Data compression was to be performed to convey all high and low frequency scene information in a 3 bits/picture element data stream.

as shown in Figure 2.1-2D. Background subtraction, achieved by filtering out low frequency variations, removes signal bias in highly illuminated imagery which might otherwise cause high amplitude signals to saturate. Amplifying the high frequency signal enhances the imagery by emphasizing signal level changes (see Figure 2.1-2E).

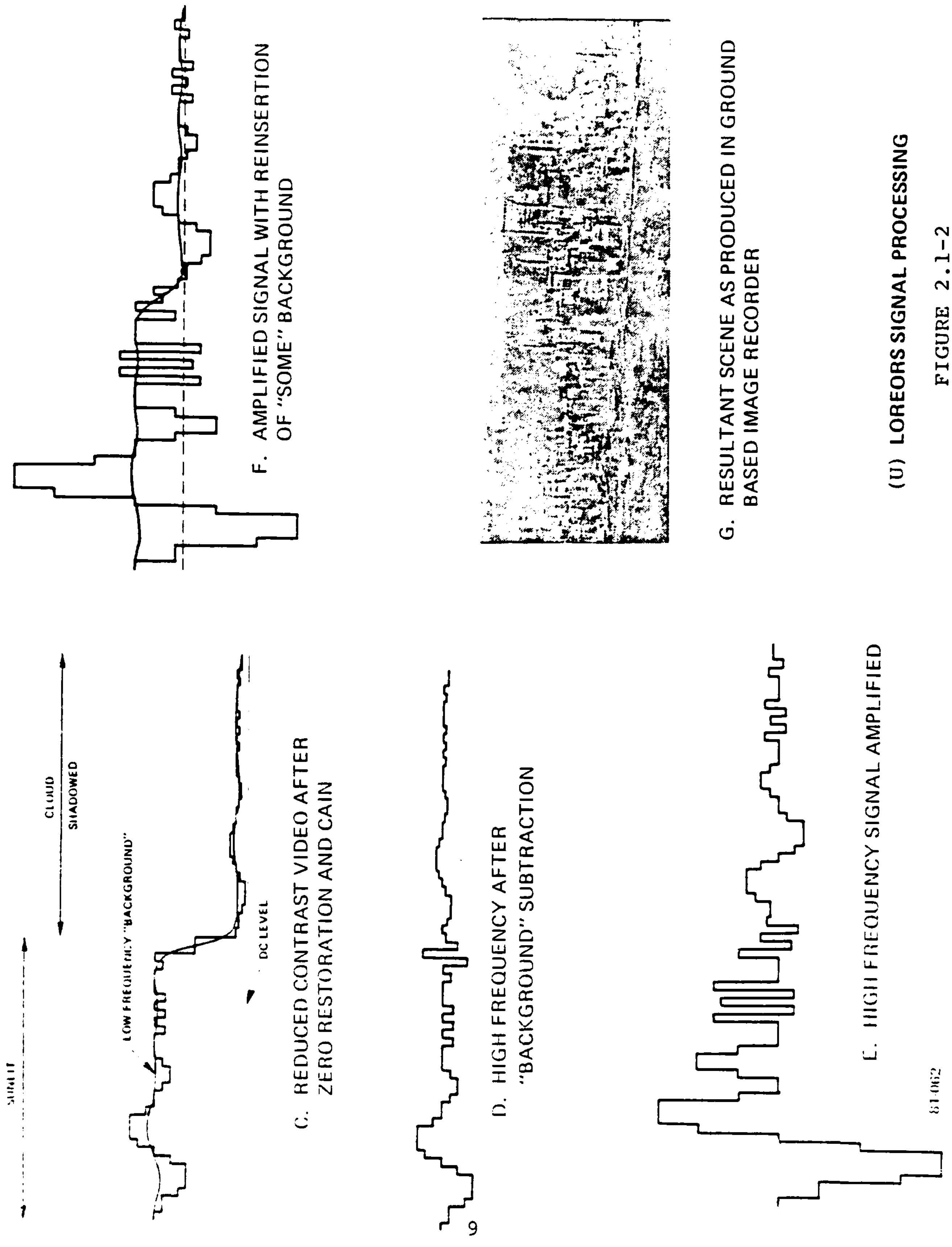
(U) After amplification a modified background level, less than the original level, is added to the video signal (see Figure 2.1-2F). The resultant reconstructed image has compressed the original contrast range allowing reproduction of the detail in the range extremes. However, more important is the ability to image an atmospherically contrast-attenuated scene, invisible to the eye, with useable detail.

(U) 2.2 LOREORS PROGRAM EVOLUTION

(U) The conceptual configuration for the LOREORS sensor was originally presented in Fairchild Imaging Systems Division's (FISD) response to a 1976 request for proposal. Fairchild proposed a Long Range Electro-Optical Reconnaissance System (Proposal No. ED-CX-409; dated 26 July 1976) advanced prototype sensor, to provide real-time high resolution imagery of low contract targets, to ground based observers.

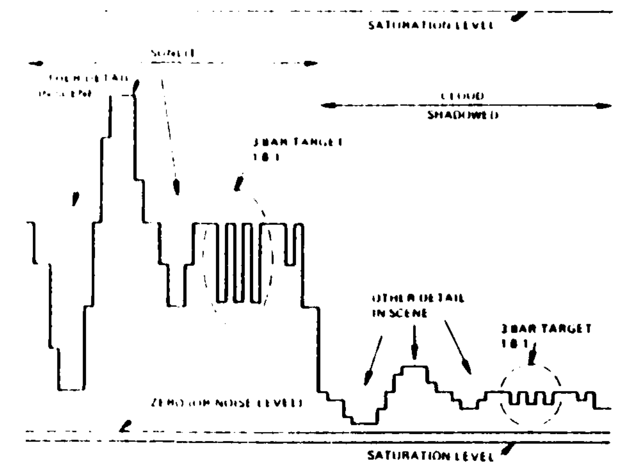
(U) 2.2.1 Proposed Concept

(U) The electro-optical sensor was a sector scan panoramic with a long focal length lens (96-inch, f/8.0). This was changed to 144" f/12 before award. The lens was comprised of 6 elements with no aspheric surfaces. This lens design, corrected for use in the silicon spectrum, took full advantage of the photodetector response.

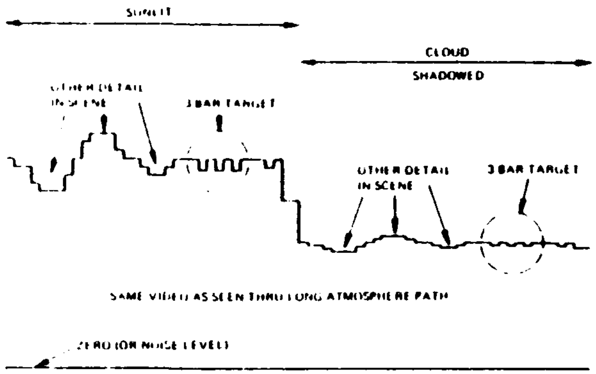


(U) LOREORS SIGNAL PROCESSING

FIGURE 2.1-2

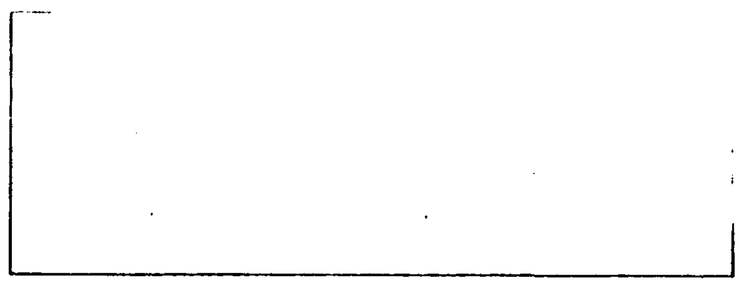


A. VIDEO LINE REPRESENTING GROUND TRUTH IMAGERY



B. TYPICAL VIDEO LINE – SHOWING CONTRAST REDUCTION

ORIGINAL IMAGE



LOW CONTRAST IMAGE

1.02:1 CONTRAST AT ENTRANCE PUPIL OF SENSOR.
AFTER 20 MI SLANT PATH

(U) THE EFFECT OF ATMOSPHERE IN CONTRAST REDUCTION

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FIGURE 2.1-1

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(U) 2.1.1 Atmospheric Effects

(U) Atmospheric effects on long range oblique imagery are illustrated by the example shown in Figure 2.1-1. In the upper right corner is an oblique scene imaged on a relatively clear day. The same scene, below, imaged through heavy haze appears invisible to the eye. Representative sensor responses typical of both scenes are shown in Figure 2.1-1 A&B.

(U) The response to the original scene, on a rare clear day, is more extensive than the range of the half-tone print; with sunlit areas extending into the saturation region and cloud shadowed areas extending to the background level. Contrast reduction due to scattering and attenuation through a long slant path reduces both the sunlit and cloud shadowed signal amplitudes proportionally.

(U) LOREORS' imaging and processing provides a method of amplifying the attenuated signal to reproduce the original scene detail. Direct amplification of the video image shown in "B" is not possible because of signal offset which must be eliminated prior to signal amplification.

(U) 2.1.2 LOREORS Signal Processing

(U) The signal offset is primarily background which saturates the image. This background level is removed by subtracting it from the video signal and restoring the video zero level of the varying signal to the electrical D.C. minimum, as shown in Figure 2.1-2C. Additional signal enhancement is achieved by removing the low frequency background signal variations prior to signal amplification

(U) 2.0 TECHNICAL

(U) 2.1 STATEMENT OF THE PROBLEM

(U) Long range oblique imaging at medium to high altitudes is limited by classical photographic aerial reconnaissance problems. High-oblique-angle imaging generally occurs through an atmosphere where the object scene is obscured by large amounts of haze and luminance scatter. Furthermore, when the reflectance from the image is low and long exposures are required, the collection system must compensate for image motion, platform vibration and vehicle and sensor environmental instability. The LOREORS solution needed to penetrate the aerosol while compensating for these classical environmental and platform-induced image degradations.

(U) Electro-optical devices developed by Fairchild Semiconductor provide the ability to overcome haze and scatter. These devices, CCD-TDI photodetectors, can gather a large signal with a sufficient signal-to-noise (S/N) ratio to allow average background subtraction from the total signal. With its sensor system designed around these TDI devices, LOREORS will image long-range targets in which the contrast level is well below the detectable limit of conventional photographic systems.

(U) Resolution and contrast rendition are the major requisites for target detectability and object recognition in the resultant image. Therefore, the long range sensing problem is resolved into; imaging low-contrast targets with high resolution while operating in a compensated environment, processing the converted signal with an adequate bandwidth and reconstituting the image for viewing.

(U) The Ground Station consisted of a 21 Channel High-Speed Ampex HPR3000 Tape Player, a Data Processor and a dry-silver Laser Beam recorder (LBR). Airborne recorder tapes containing imagery data, control information and data annotation were replayed through the Tape Player. Nineteen channels were used to recapture imagery and 2 channels were devoted to control data.

(U) Adding Sharp data to updated Unsharp data in the Ground Data Processor recreated enhanced image data. Recomposed annotated data were then fed to a Laser Beam Recorder which reproduced images on dry-processed silver film.

~~(C)~~ Final enhanced images showed good detail in scenes with original contrast ranges of less than 1.005:1. Thus the ability of the system to provide intelligence imagery from scenes having apparent contrast well below the useful threshold of conventional photography was successfully demonstrated.

(U) The Video Processor Electronics contained both analog and digital video signal sections. Eight identical channels of analog electronics filtered, amplified and conditioned the video from each of the 8 (imaging plus IMC) CCD detectors. Because pixel-to-pixel nonuniformities could cause variations in output greater than the "information" fluctuations, it was necessary to calibrate and electronically compensate them on an individual pixel basis. Background subtraction was performed to remove the D.C. "haze" level present in each image pixel.

(U) In the digital section the video signal was enhanced. A running average was maintained of the "pixel of interest" minus the average of the 8 surrounding pixels. This "non-sharp-masking" technique allowed high-frequency variations (edges) to be automatically enhanced. The 8 pixel average data were also recorded in a compressed form for use in subsequent ground station image processing. Thus low spatial frequency data with large amplitude excursions were separated from the high spatial frequency, low amplitude detail data and labeled "Unsharp Data". The high frequency signal was labeled "Sharp Data". The data were then transmitted to the digital tape recorder for storage.

(U) The Computer subsystem was controlled by a Hewlett Packard HP1000 Computer assisted by a HP7900 disc drive, a HP2645 CRT monitor and input terminal and a HP2631 line printer. This Computer was the primary system controller. It contained the mission plan, power application sequence, tests and calibrations of the CCD chips, equipment tests, air pressure profiles, target selection, autofocus correction, generation of servo position commands, display system operation controls, logging data commands and commands for maintaining the system interlocks.

(U) The system was disassembled and focal point tests were made with and without the field flattener and simulated prism assembly. In addition, the mechanical subassemblies were remeasured to confirm that machining and/or assembly errors were not source of the problem. It was determined that the shift was caused by a 0.22 inch error in the position of the focal plane and a 0.5 inch deviation in focus caused by the radius and index variations in the optical design.

(U) A design study was initiated to find the most cost-effective effective solution. It was determined to shorten the aft section of the lens barrel. This necessitated:

a) Disassembly of the system down to the lens barrel assembly.
b) Cutting off the aft lens barrel and machining a pilot surface for an insert flange.
c) Machining an insert flange.
d) Installing the insert flange on its aft barrel and final machining.
e) Reworking the isolation mounting pads.
f) Cutting a section out of the center of the thermal shroud and rewelding the two halves.
g) Reassembling the entire system.

~~(C)~~ The remaining system tests encountered the "normal" run of debug tasks such as:

- Preliminary low contrast imaging test were made. Performance was limited to 1.05:1 contrast targets by noise levels in the imagery inconsistant with the measured system noise levels.

Investigations showed that considerable spatial noise was being inserted by the test collimator. The collimator light source was removed and the noise contribution of the collimator source corrected.

- Investigations made to improve the CCD calibration accuracy led to two changes. First, the timing between the selection of level of integration and the collection of video calibration data was found to be marginal and was increased. Second, the number of video samples collected for calibration was increased from 32 to 128 to minimize the effect of noise.

- Investigations of the calibration accuracy further uncovered a procedural problem with the dark signature correction alignment procedure. The dark signature of a small number of pixels on each CCD is lower than the signature of the masked reference pixels. Biasing the lowest of these dark pixels to ground (rather than to the masked reference pixels) led to gain offset variations as integration levels were changed. The alignment procedure was corrected to elminate these variations.

- Two A/D converters were found to be defective. Newly published application notes from the manufacturer prescribed limitations on the soldering time and temperature during printed circuit board installation of these devices. Since these limitations are more stringent than Fairchild standards for normal pc board installation and, in addition, were considerably more restrictive than installation standards normally associated with this class of device, it was suspected that the rash of A/D failures were the result of the newly-published fabrication restrictions being exceeded during assembly.

- During system test, the light signature correction was found to be accurate to only one percent instead of the design goal of one-tenth of one percent. Investigation of the signature correction subsystem uncovered an error in the signature correction algorithm. The error was corrected and the light signature correction error was reduced to approximately three-tenths of one percent.

- A fifteen degree skew in the system imagery was traced to misalignment of the sensing head and scan head and unbalance of the sensing head due to removal of the sensing head stops. The stops were replaced, and the sensing head was rebalanced.

- LBR hard copy of low contrast imagery exhibited streaking along the scan direction. Investigation showed this was due to errors generated in the unsharp mask. The problem was tracked to erroneous data transfer from card to card by the low power schotky logic. Reduction of loading on data lines and the addition of buffers on the clock lines eliminated the problem.

(U) 2.2.4.4 System Delivery

(U) System tests were completed during December of 1979 when the Airborne system was shipped to WPAF for installation into the aircraft and the start of flight tests.

(U) The Ground System was held until early February to incorporate some final changes and to allow some additional image testing and evaluation.

(U) 2.3 FLIGHT TEST PROGRAM

(U) The flight test program was conducted as scheduled during the second quarter of 1980. With the assistance of Air Force personnel the system was preflight tested and mounted in the C141 aircraft for operational tests. The initial problems encountered were related to the targeting of the system. Imaging data were obtained from the first mission. Because of the complexity of this system (and with the advantage of hindsight) it is believed that a pre-test flight checkout program would have improved the overall results of the flight test program.

(U) The final results of the LOREORS tests, obtained as a result of the evaluation of imagery, demonstrate that the system succeeded in its purpose. High-resolution imagery possessing sufficient detail for the detection and recognizability of selected targets at long ranges was obtained under conditions of extreme haze. Enlargements of target areas show that the resolution and enhanced gray scale provide the image acuity required for tactical target detection and object interpretation. Examples of the photography and the contrast rendition are shown in Appendix C. Typically, a roadside household mail receptacle can be recognized and easily identified from an enlarged reproduction imaged at an altitude of 31,000 feet, at a slant angle of 60 degrees penetrating haze levels from a range of ten nautical miles.

(U) As suggested above, these results were not obtained without some initial difficulties. The original flight plan, with missions all over the United States, had to be scrapped because of the operational problems encountered.

(U) Equipment failures and flight condition inadequacies became apparent during the first flights. As a result, a substitute, less-extensive local mission flight plan, was instituted to provide the opportunity to correct the equipment problems. Imagery was obtained from almost every flight.

(U) The flight test program consisted of twenty-three missions. Imagery obtained from the first flight on March 19, 1980 was recorded with a loss of forward motion compensation and a frozen scan air bearing. Even so, a sufficient quantity of image signal was recorded to provide a reproducible image from low contrast targets.

(U) During the next few flights the mission was primarily concerned with the task of correcting sensor problems. The system pointing and stabilization was affected by the accuracy and instability of data from the inertial navigation system. Problems were also encountered with the autofocus and exposure systems. About half way through the flight test program most of the symptoms had been identified and corrections applied. Since the majority of the problems were related to the peripheral electromechanical sensor support equipment, imagery with various levels of quality was obtained. As equipment fixes and compensations were incorporated the quality of the imagery, especially with regard to resolution improved.

(U) There was never a problem with the quality of the image contrast. Contrast goals were achieved and demonstrated early in the program and consistently thereafter.

(U) Improvements in the targeting control capability of the system improved resolution. Results obtained from the last few flights demonstrate the dramatic ability of LOREORS to penetrate haze and record target images. A description of these flight tests with an evaluation of the results and examples of imagery are given in Appendix C.

(All of section 3 is unclassified)

3.0 THE LOREORS SYSTEM

The configuration for the Long Range Electro Optical Reconnaissance System was comprised of eight subsystems and components. Of the eight, four are essential for imaging and signal processing. These components are:

a) The Imaging Sensor Unit

b) The Servo Box Unit

c) A Two Bay Processor Console

d) A Dual Bay Computer Console.

The remaining four components comprise peripheral support equipment:

a) A CRT Data Terminal

b) A Two-Bay Air Conditioner

c) An Air Compressor

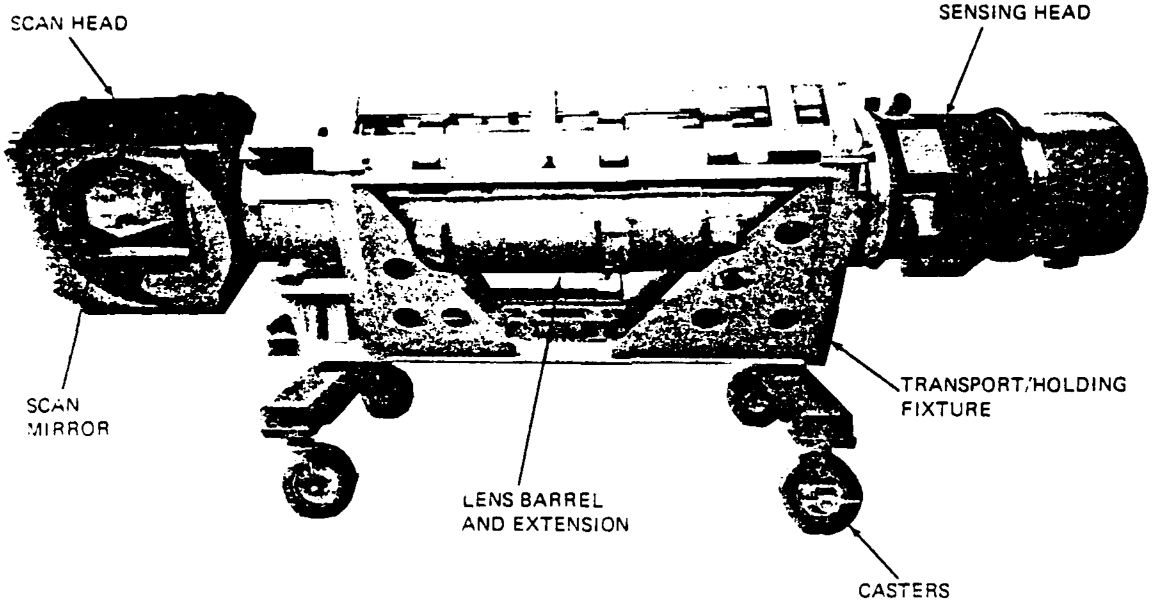
d) A Ground Station Data Processor.

All of this equipment with the exception of the Ground Station equipment, was used in the airborne LOREORS configuration.

3.1 SUBSYSTEM COMPONENT DESCRIPTION

3.1.1 Imaging Sensor Unit

The Imaging Sensor Unit shown in Figure 3.1-1 is shown without the ancillary manifolds and tubing normally required for distributing environment-control air conditioning. Extending over thirteen feet in length and weighing over 2000 pounds, the main assemblies of the sensor are the scanning head, the lens barrel and barrel extension and the sensing head. The sensor is shock mounted within a transportation/holding fixture which is equipped with casters to facilitate its transport.



(U) FIGURE 3.1-1. SENSOR

The functional components within the Sensor are the Optical system and the focal plane assembly. The Optical system is composed of the aiming mirror and the focussing lens train. The focal plane assembly, upon which the target is imaged, is comprised of the beam sharer, the six TDI-CCD detector chips and the associated electronic control components. Drive components for aiming and scanning are also housed in the Sensor.

3.1.2 Servo Box Unit

Servo control components required for the Stabilization and Control Subsystem are housed in the Servo Box Unit. There are three control servos in the imaging system, the Scan Servo, the Forward Motion Compensation (FMC) Servo and the Sensing Head Servo. The power supplies and power amplifier for the Sensing Head servo are housed within the Servo Box along with converting preamplifier and multiplexer cards.

The Servo Box Unit shown in Figure 3.1-2 also contains the electronic components which support the Inertial Navigation System (INS). Shock mounted in a frame which is tied to the vehicle floor, this Servo housing measures three feet wide by two feet deep by one foot high.

3.1.3 Two-Bay Processor Console

Constructed in a dual console housing comprised of a steel structure 50 inches high by 53 inches wide and 29 inches deep, the Processor Console contains all of the electronic circuitry

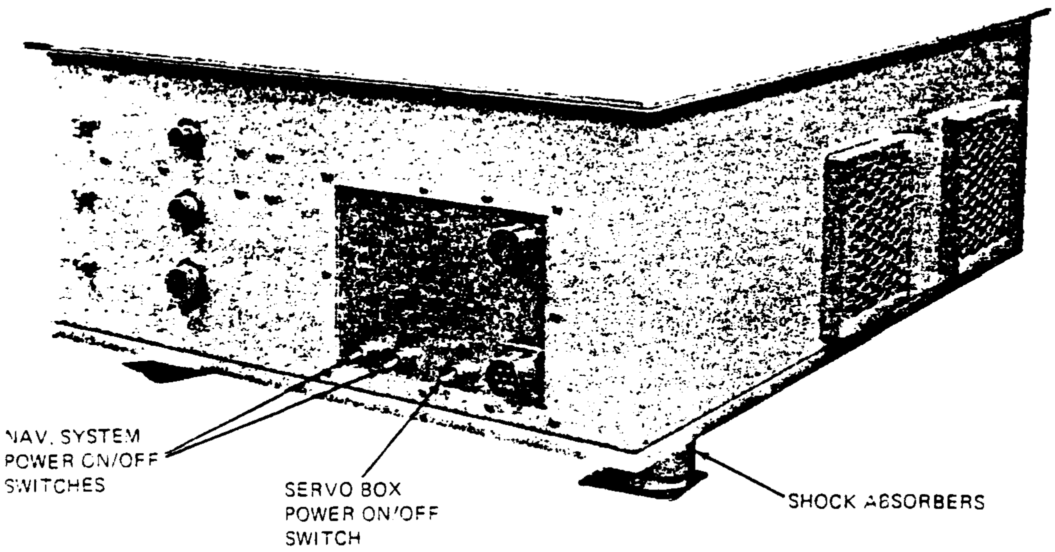


FIGURE 3.1-2. FLOOR MOUNTED SERVO BOX

required to process the video signals for the IMC/FMC signal channel and the six video image signal channels. As shown in Figure 3.1-3, the Processor contains the signal channels in the right compartment and a power supply assembly in the left cabinet. For stability in the airborne platform this console is shock mounted in a frame which mounts to the installation floor. All subassemblies and components are accessible for operation and maintenance through double doors on both the front and back of the cabinets. A triple-tier card rack contains the analog and digital video signal processing electronic cards. A single card rack contains the IMC/FMC detection cards. A power supply, which provides all of the power levels required for console operation, is on a separate chassis. Cooling components required to circulate air within the cabinets are contained in the lower console area.

3.1.4 Dual-Bay Computer Console

As shown in Figure 3.1-4, the Computer Console is also contained in a mounted standard-size dual cabinet which is shock-mounted in a ancillary frame for stabilization while airborne. Access to the computer subassemblies is through the front of the Console (with the front protection doors open). These components also can be slid forward for front maintenance. Located in the left section (facing the console) is a Hewlett Packard-1000 minicomputer which operates with a HP 7900 disk controller and power unit mounted over it. A Data Logger Unit is also included to store recorded operational data. Mounted in the right hand console section are the Ampex airborne digital recorder used to store the imagery data gathered during a mission and its support equipment.

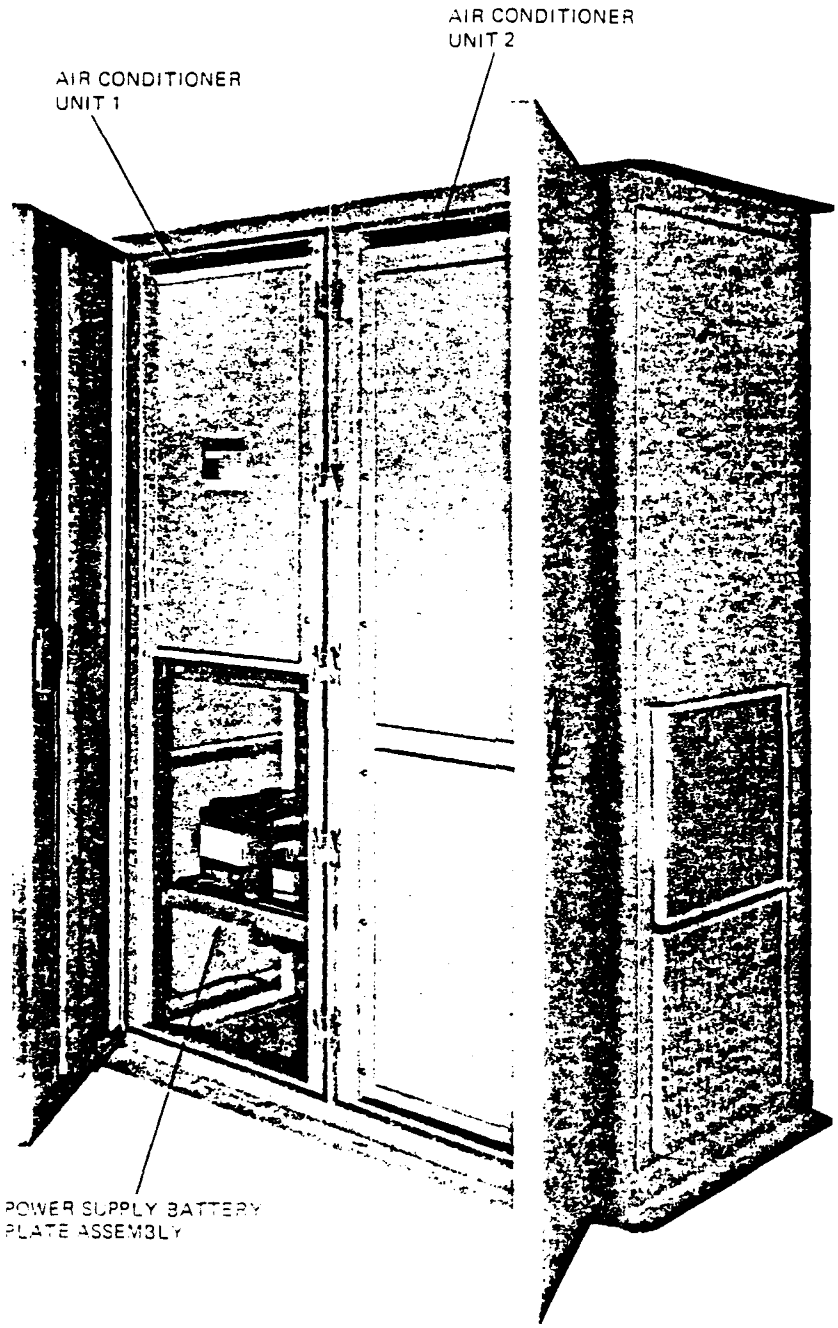


FIGURE 3.1-3. AIR CONDITIONER

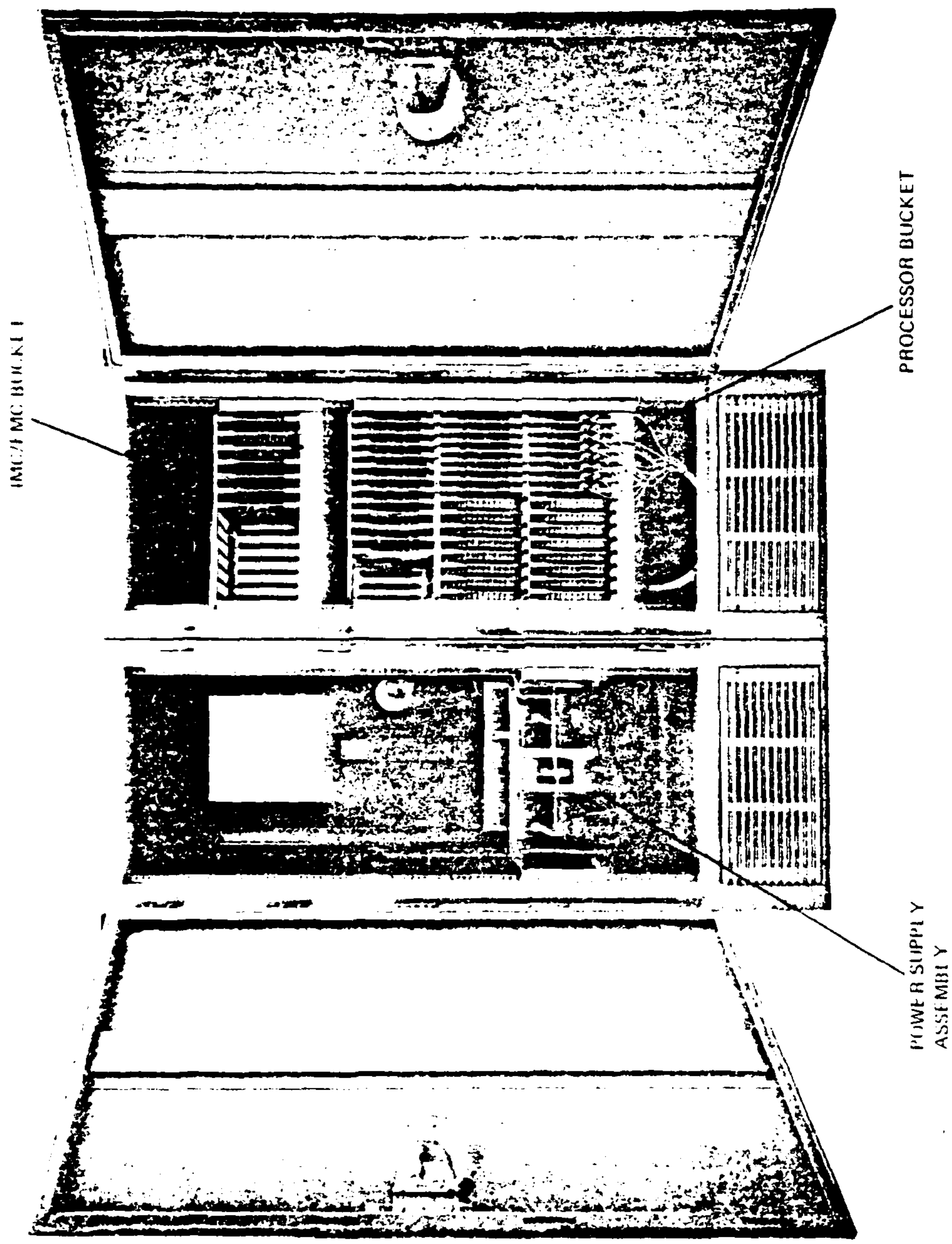


FIGURE 3.1-4. PROCESSOR

3.1.5 Support Equipment

Ancillary equipment utilized to support LOREORS imaging operations consists of the CRT Terminal shown in Figure 3.1-5 which provides an operator interface with the system computer, an Air Conditioner used (see Figure 3.1-6) to circulate conditioned air, either heated or cooled, to maintain a constant thermal level, an Air Compressor (see Figure 3.1-7) to supply the air current required for the Sensor air bearings and a Ground Station Data Processor shown in Figure 3.1-8 used to reconstruct the image data into hard copy.

3.2 FUNCTIONAL DESCRIPTION

A general description of the LOREORS functional operating areas are presented in the following: The main functional subsystems of LOREORS are:

a) The Optical System which images the target on the focal plane
b) The Stabilization and Control System used to aim the Sensor at the target, scan the target and to neutralize relative motion between the target and the Sensor
c) The Environmental Control which isolates the Sensor from its surroundings and compensates for external inputs which degrade the image
d) The Auto Focus System which corrects for focal error
e) The Sensing Head and Video Processor which converts the optical image to an electrical signal and then processes the video signal data recording
f) The Computer which controls all system operations
g) The Ground Station used for image processing and hard copy image reconstruction.

The sensor lens forms an image of the transmitter grating on the receiver grating. Oscillating the scan mirror causes the image of the transmitter grating to be swept across the receiver grating. With the gratings and CCD array all located in the focal plane, best-focus grating and CCD imagery are obtained simultaneously (for infinity focus).

The transmitter grating image best-focus condition results when the highest instantaneous maximum light passes through the receiving grating, as collected by a large area silicon photodiode. Defocus conditions result in lower instantaneous maxima. This is shown in Figure 3.2.4-2. A plot of maximum response vs. defocus for a given grating pitch is shown in Figure 3.2.4-3.

The actual grating pitch is chosen to yield an effective defocus range of approximately ±0.016-inch. This choice provides sufficient sensitivity to attain a practical focus correction of ±0001-inch (1/3 of a 1/4 wave rayleigh tolerance).

Autofocus correction requires two steps, (1) acquisition and 2) vernier correction. Acquisition locates the "approximate" best focus position within the total back-focus correction range available. It is estimated that a range of 0.250-inch is required (including ground test conditions). Acquisition is accomplished by moving the focal plane carriage to one end of its 0.250-inch travel. With the scan mirror oscillating, and the carriage moving at approximately 0.010-inch steps, the photodiode output is read and stored. After 25 (0.250 inches) readings have been completed, the carriage is returned to the position producing the maximum response.

AUTO FOCUS

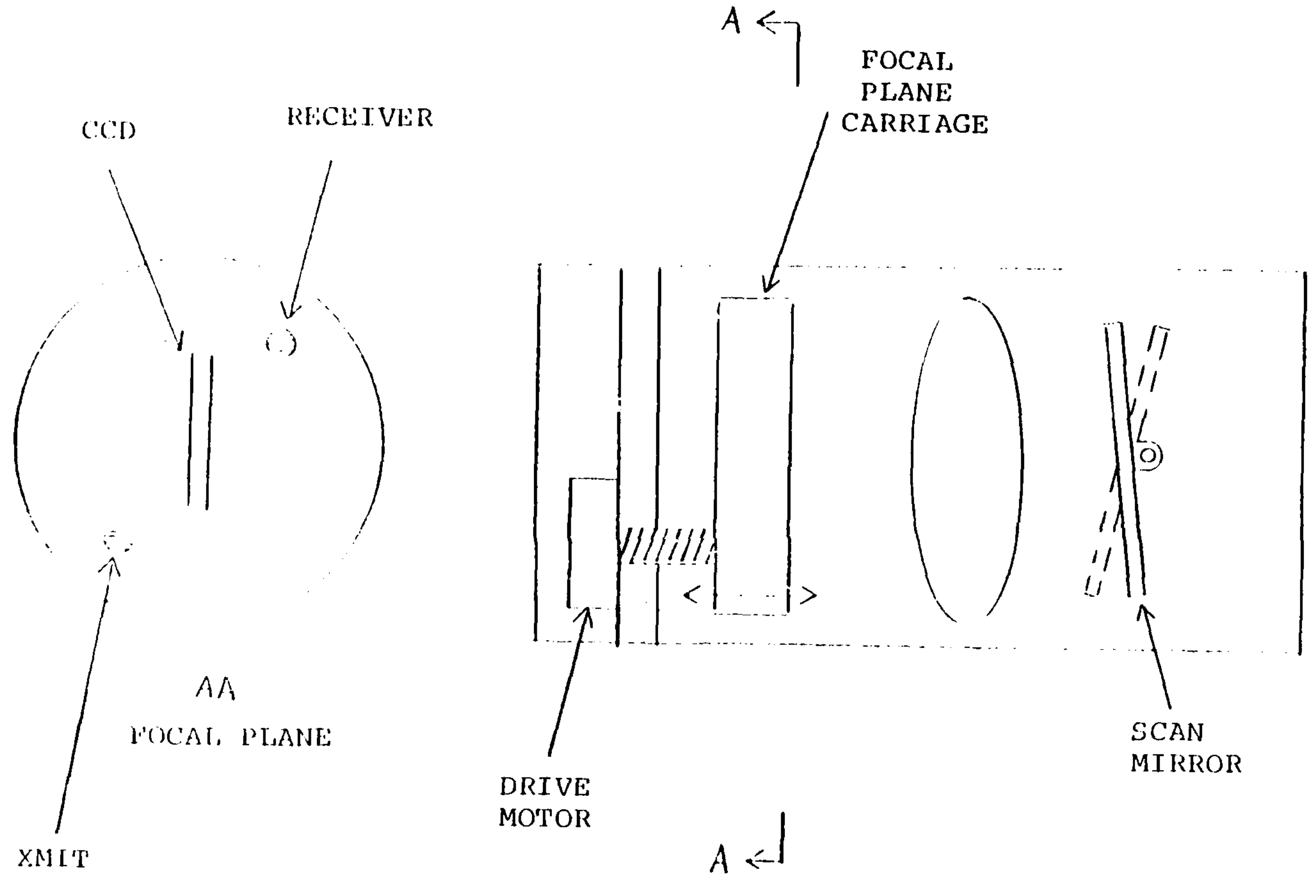


FIGURE 3.2.4-1

pressure conditions. This refocussing ability minimizes the need for long soak periods in controlled thermal environments before peak imaging performance can be realized. The autofocus system senses deviations in the back-focal distance of the lens, which result from temperature or pressure changes and thermal gradients, and automatically restores the camera to a best-focus condition.

The autofocus system consists of an oscillating flat mirror, and an optical transmitter/receiving grating pair, which is mounted on the focal plane. The focal plane is mounted on a servo-driven carriage with an encoder for position feedback. Based on the signal from the grating pair, the computer determines best focus and drives the carriage to the proper position.

Autofocus system operation is achieved using the camera's own optical elements (lens and scan mirror), as shown in the optical schematic of Figure 3.2.4-1. The grating pair and the CCD array are mounted on a carriage, coupled to a precision drive mechanism, capable of adjusting the back focal distance over the requisite range.

A light source illuminates the transmitter grating. Light passing through this grating is transmitted through the lens, reflected back by the mirror, retransmitted through the lens and returned to the receiver grating which has a photodiode detector located behind it.

system designed to provide approximately equal deflection constants in each of the three orthogonal directions. This is combined with a dry friction type of damping and a resilient, snubbing limit-stop. The Temperature Control System provides both heating and cooling in such a way as to maintain the entire camera as nearly constant and as close to a fixed temperature as possible. The air conditioner console, supplies the camera with pre-conditioned air. This air is circulated between the lens barrel and the thermal shroud, around the sensing head, and around the scan head. The circulated air is routed back to the air conditioner for reconditioning. In addition, the sensing head has eight thermo-electric coolers strategically placed to maintain proper sensing head temperature. The entire camera temperature is monitored by thirty thermo-couples distributed through the camera sensor and can be read out on the CRT Data Terminal.

The focal plane, located in the sensing head of the Sensing Unit, is conditioned by a combination of the thermo-electric devices and the circulating conditioned air. Three thermocouples are located on the focal plane to enable monitoring of the Sense Head temperature. These thermocouples are part of the system monitoring system.

A total of thirty iron-constantan thermocouples are located throughout the Sensor to monitor temperature. Besides the three in the focal plane, nine are located in the Scan Head and 18 around the lens barrel. These monitors are read by a data logger.

3.2.4 Autofocus System

The Autofocus System automatically compensates for deviations in the Sensor optical characteristics to provide the best infinity image focus under a broad range of temperature and

Navigational (NAV) data consisting of target location and inertial reference data are fed into A/D converters. These data, related to the aircraft position and orientation based on heading pitch and roll information from the INS, are synchro generated and converted to digital form in the Servo Box Unit. Altitude data are similarly generated from a radar altimeter. Converted NAV data are multiplexed with inputs from the three position encoders. The encoders indicate the present Scan, FMC, and Sensing gimbal orientation. Comparing the input commands with the feedback, the computer generates updated, current commands to drive and reposition the gimbals as required.

FMC commands are generated from present vehicle V/H and desired Scan angle coverage. The FMC inserts corrections for aircraft advance driving the Scan gimbal at a one degree per second scan rate.

During image scan, the focal plane assembly in the Sense Head must be locked to the mirror in the Scan Head. This is accomplished by slaving the Sensing servo to the Scan servo. The feedback from the Scan encoder is added to the signal from the Sense encoder in a differential amplifier and then added to the computer sense command, effectively locking-in the Sense torquer.

3.2.3 Environmental Control System

The Environmental Control consists of a vibration and shock system and a Temperature Control System. Protection from vibration and shock is provided thru the use of vibration filter mounting devices between the image sensor housing and its frame. These Vibration mounts contain a spring suspension

SERVO POINTING

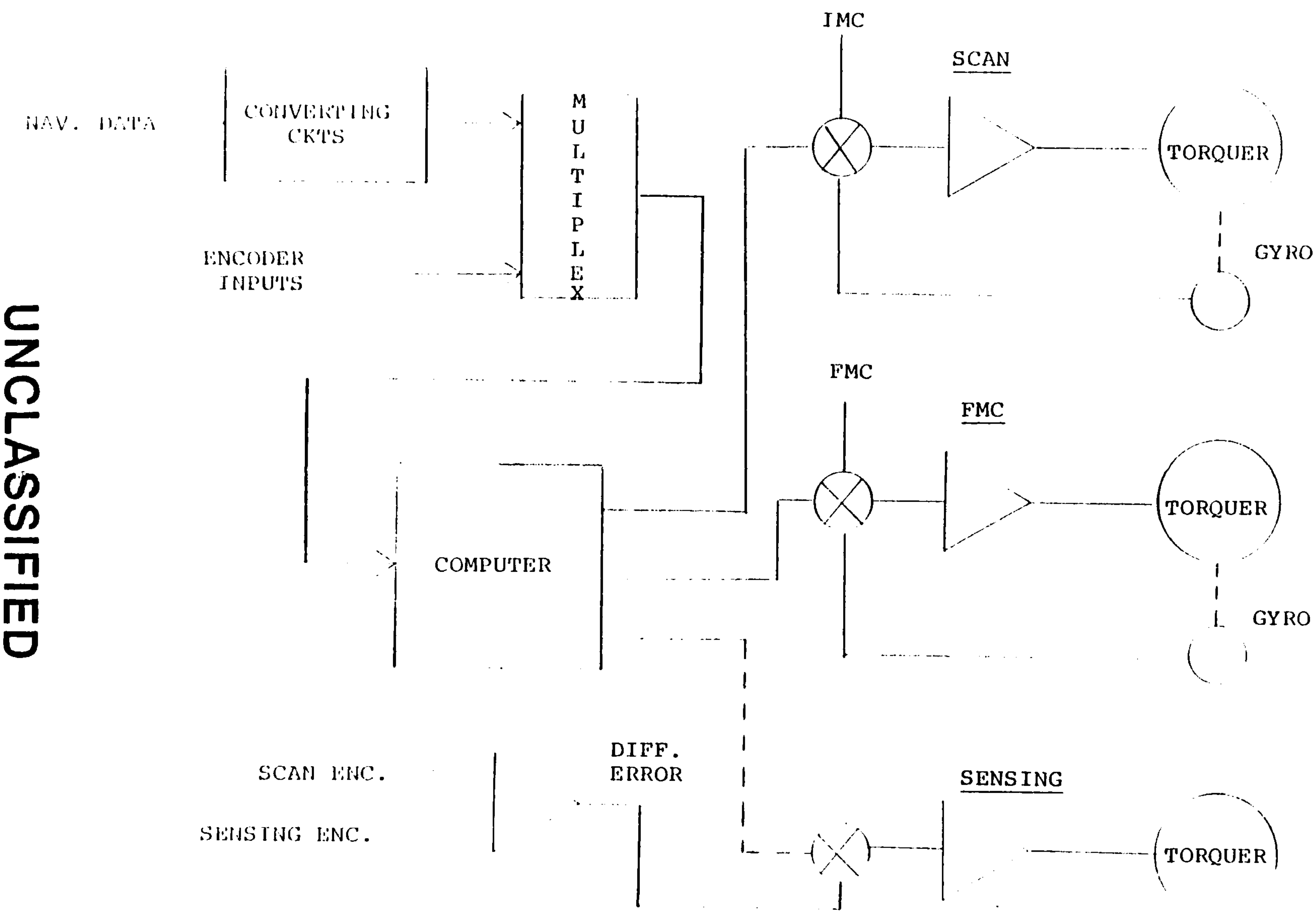


FIGURE 3.2.2-2

are achieved by rotating the Scan Head relative to the Sense Head. An encoder on the Scan Assembly generates scan position feedback and a roll rate gyro generates roll rate feedback signals. This rate gyro, mounted with its input axis parallel to the vehicle roll axis, is connected to the Scan gimbal; forming a rate feedback loop used to maintain a constant image scan rate relative to inertial space. The air bearings at each end of the Sensor link the Scan gimbal to the Scan Assembly and the Sense gimbal to the Sense assembly and are supplied with air from the Compressor Unit.

Pitch stabilization is achieved by summing vehicle generated pitch signals with Scan Command signals. An encoder on the Sense Assembly and a rate gyro on the Sense gimbal generate the pitch position and rate feedback signals.

Yaw stabilization is achieved by summing vehicle yaw signals with FMC Command signals. Feedback in this loop is also generated using an encoder for positional location and a rate gyro for rate signals. FMC gimbal inputs to the FMC torquer rotate the pointing mirror, which is decoupled from the Scan gimbal through a roller bearing.

3.2.2.2 Control Signals

Mirror pointing command and control is generated by the system computer based on target location, aircraft position and feed-back offset information. Aiming of the mirror is performed by servo positioning as determined by computer generated information. This is shown in Figure 3.2.2-2.

LOREORS SYSTEM

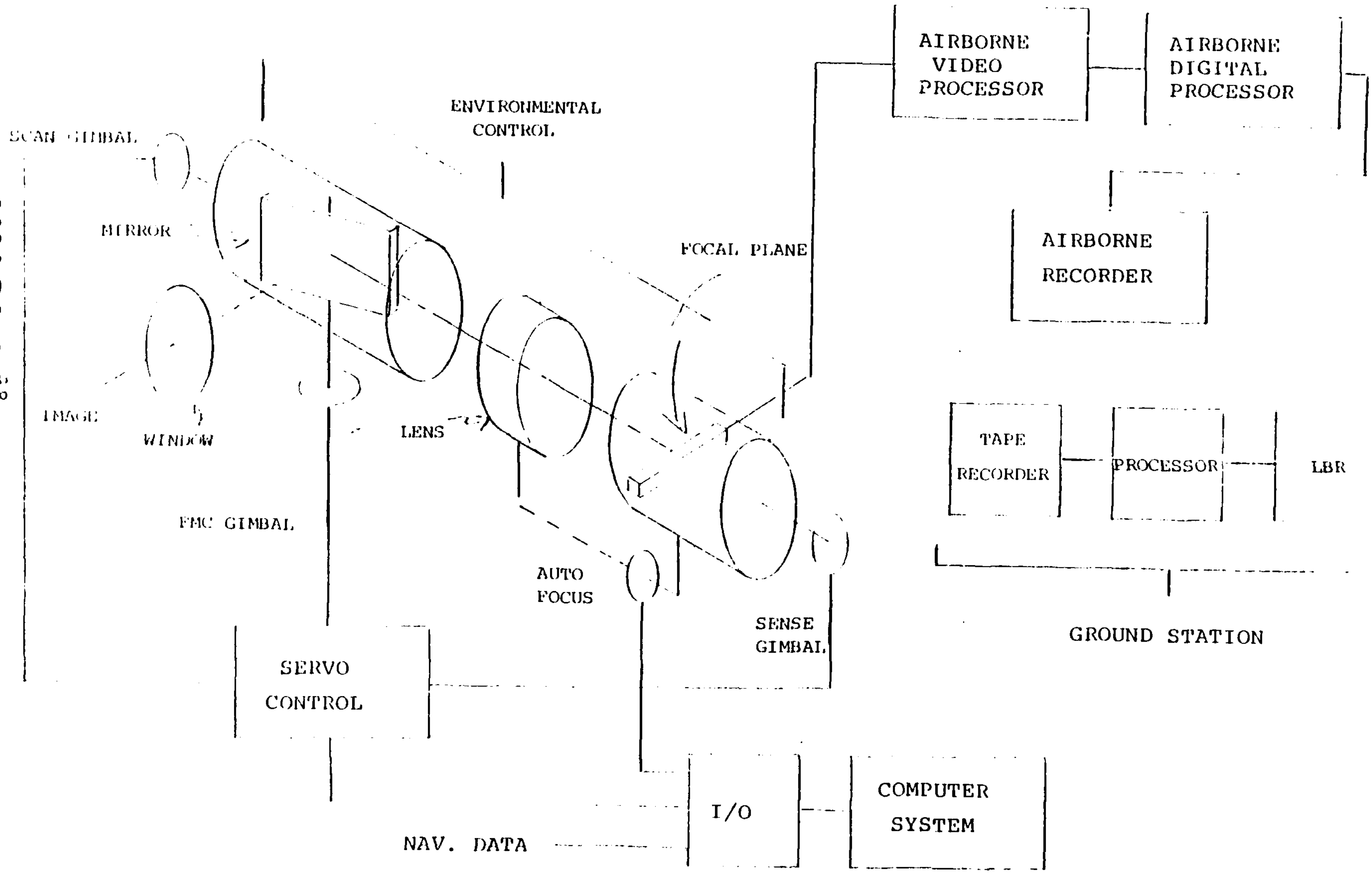


FIGURE 3.2.2-1

CCD's averages about 68%, whereas the diffraction limit is 73%.

Images are focussed upon a beam sharer, (described in the papers In Appendix A) where it is split into sets of transmitted and reflected beams. These ray groups focus upon the odd and even CCD chips in the focal plane to produce sections of the image scan line. These sections are then combined to produce a continuous scan line.

Cross-track coverage is obtained by rotating the scanning mirror about the aircraft roll axis to produce a cross-track scan. Forward motion compensation for vehicle advance during the scan is obtained by supplying an opposite drive into a mirror servo to maintain a constant pointing angle. Focus is automatically pre-adjusted to an optimum setting prior to an imaging run to compensate for the effects of residual thermal gradients, wave front errors and variations in slant range.

3.2.2 Stabilization and Control Subsystems

The Stabilization and Control Subsystem utilizes the Scan, Sensing and Foward Motion Compensation servos for both stabilization and target aiming (see Figure 3.2.2-1).

3.2.2.1 Stabilization

Stabilization of roll motion is accomplished by adding roll motion correction signals to Scan Command signals. Scan Command signals are developed as a result of rate and position inputs. The image sensing assembly,mounted with its scan axis parallel to the vehicle roll axis, is rotated within the Scan and Sense Gimbal air bearings at each end of this assembly. Roll corrections

3.2.1 Optical System

LOREOR'S Optical system uses a scanning mirror to view the objective scene through the aircraft window, which is considered part of the optical train. The mirror folds the optical path through a 90° angle directing the imaged scene toward the lens. A near diffraction limited 144 inch (3.66 meter), F/12 lens, with a 96 inch (2.44 meter) overall length was designed to cover the entire silicon spectrum. All of the lens elements are air spaced spherical elements. The entrance pupil of the lens lies at the first surface of the objective group. This offers a significant advantage with respect to the scanning mirror operation, since the field of view divergence starts at the entrance pupil and thus allows the use of a smaller scanning mirror than would otherwise be possible.

The lens is of an extreme telephoto form, consisting of a six element objective group, a three element negative Barlow group and a single element field flattner near the focal plane. The objective group has a focal length of approximately 72 inches. Its image serves as a virtual object for the Barlow. The combination produces a real image 96 inches from the entrance pupil with an effective focal length of 144 inches. This lens is completely unvignetted over its field of view of 5.86° (0.102 radian). Its image format is 374.4 mm.

Modulation transfer function performance across the field of view is equal in both directions throughout the field. The MTF at 25 line pairs per millimeter, the Nyquist limit of the imaging

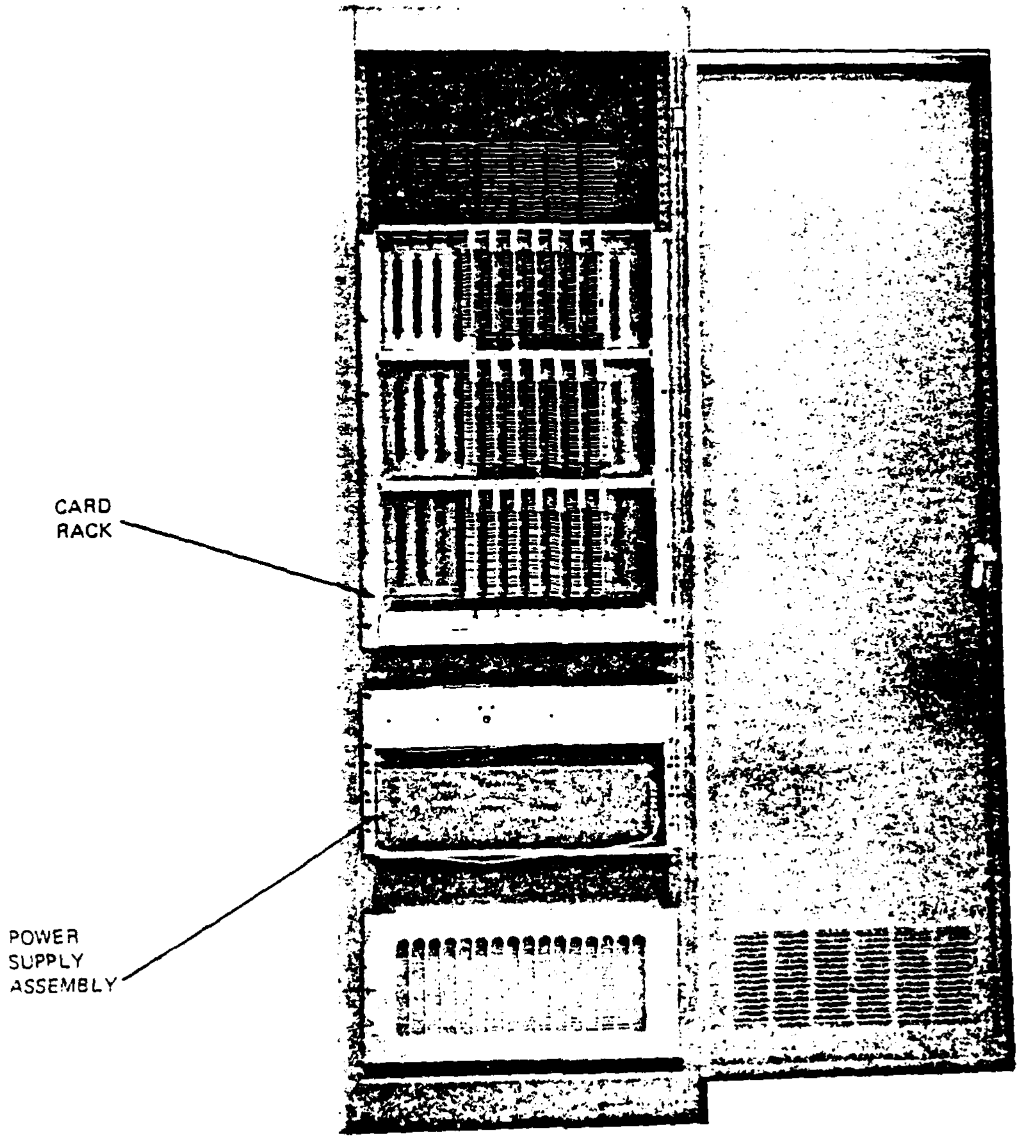


FIGURE 3.1-8. GROUND STATION DATA PROCESSOR

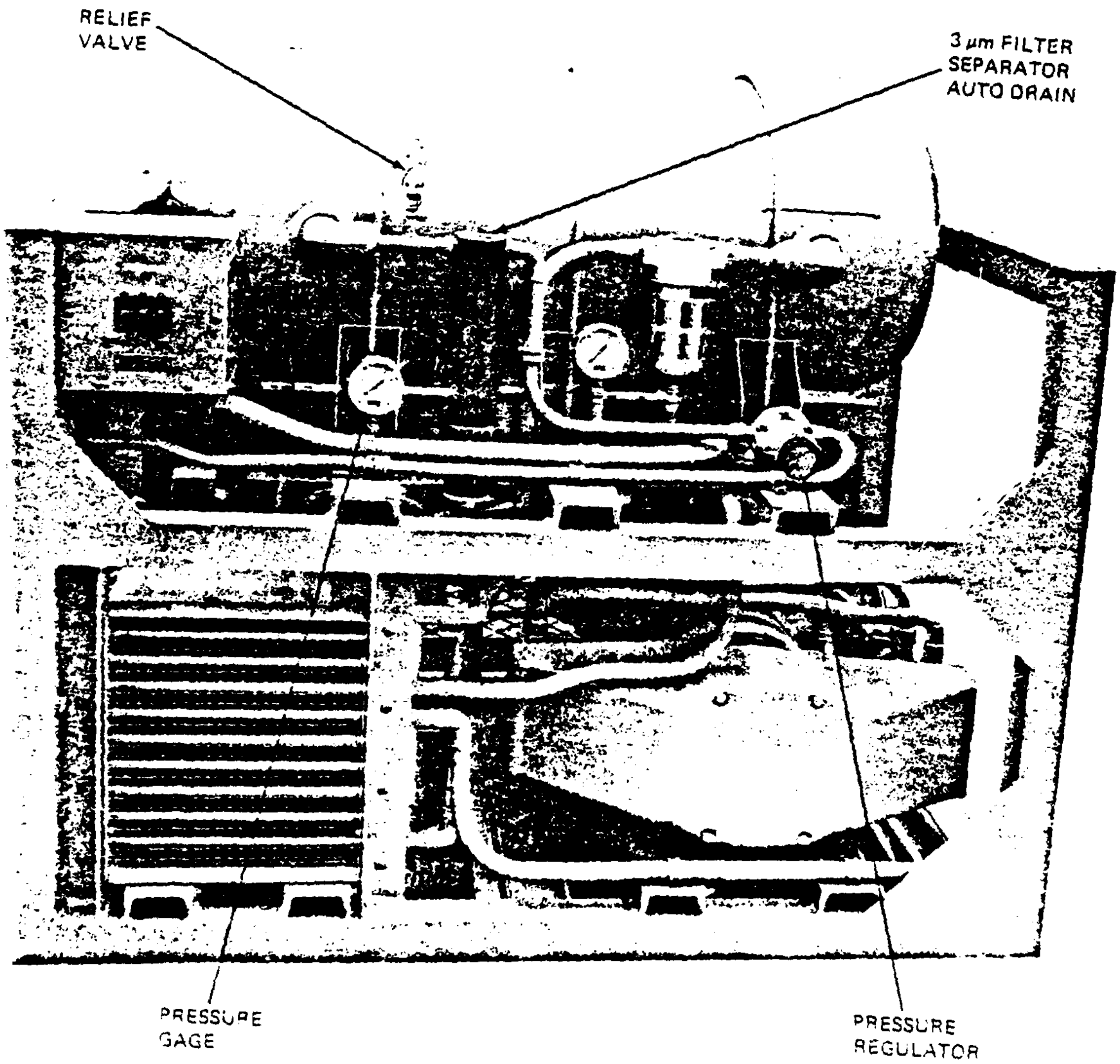


FIGURE 3.1-7. AIR COMPRESSOR

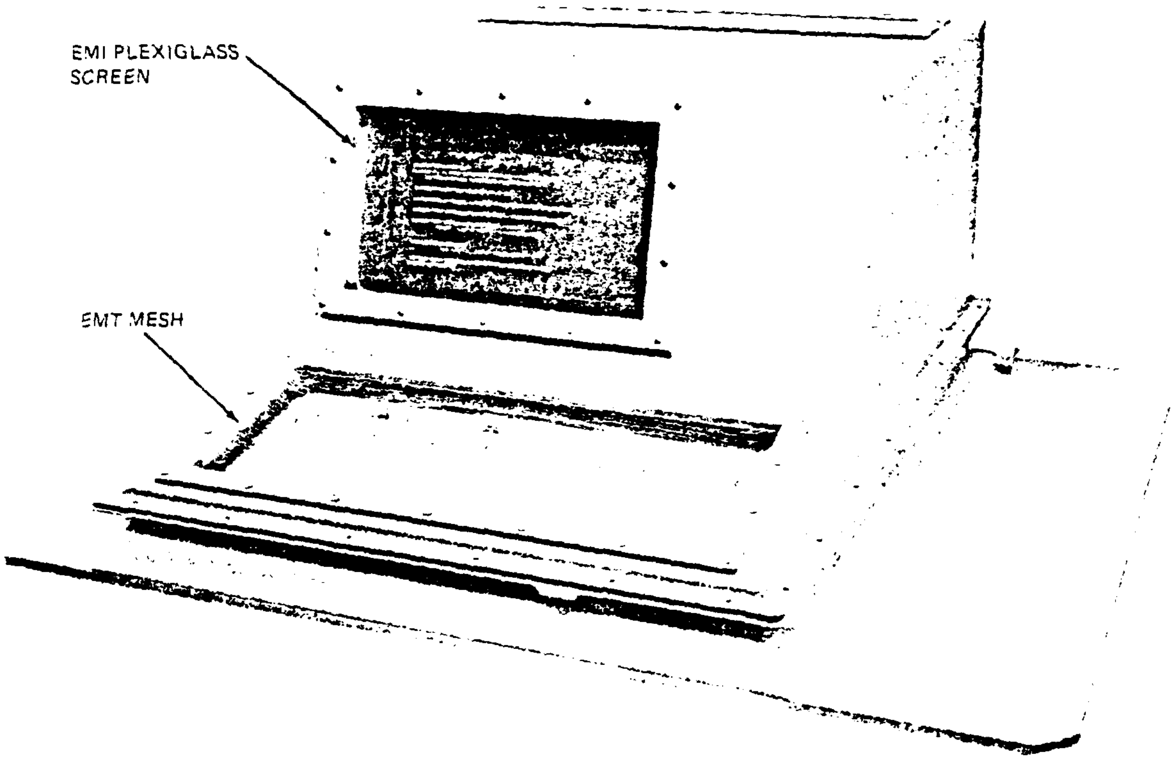


FIGURE 3.1-6. CRT TERMINAL

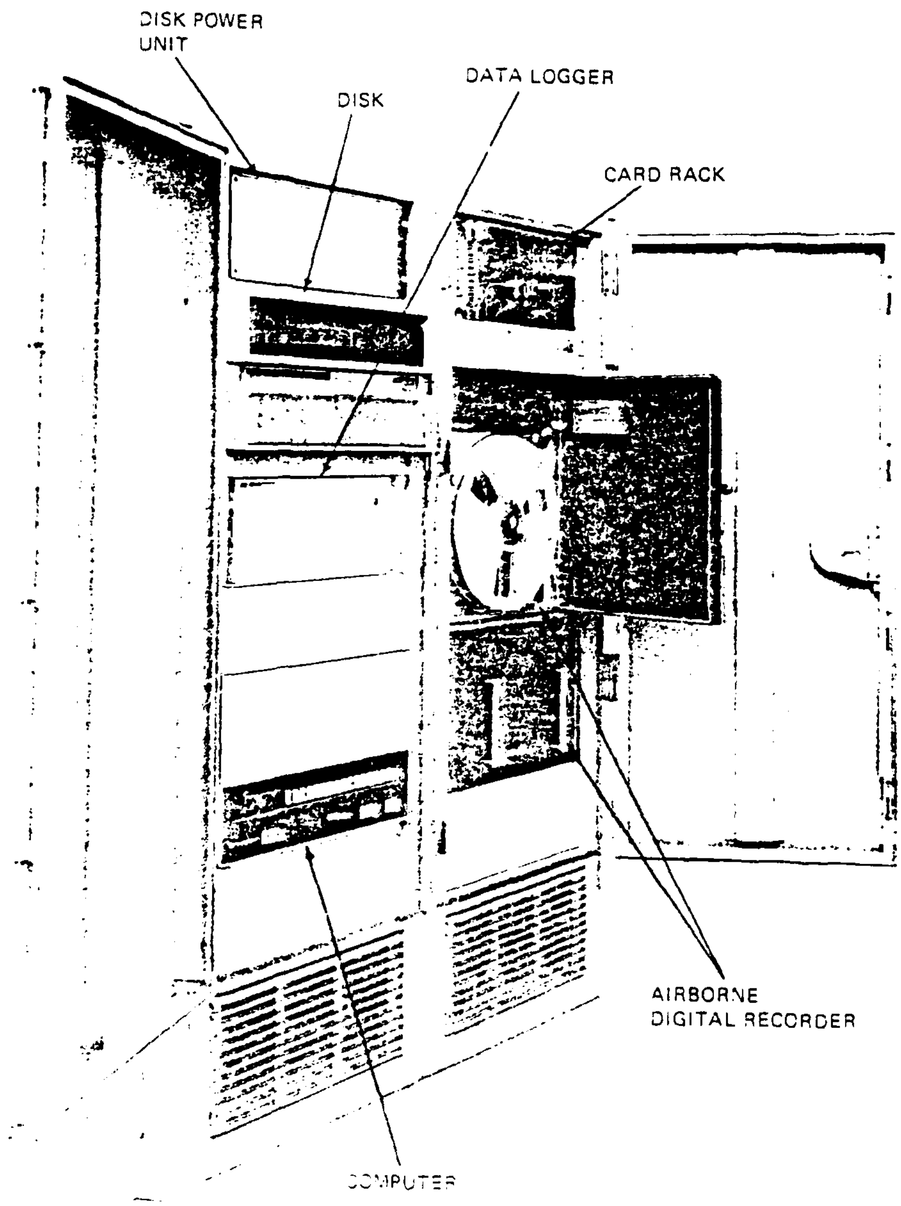
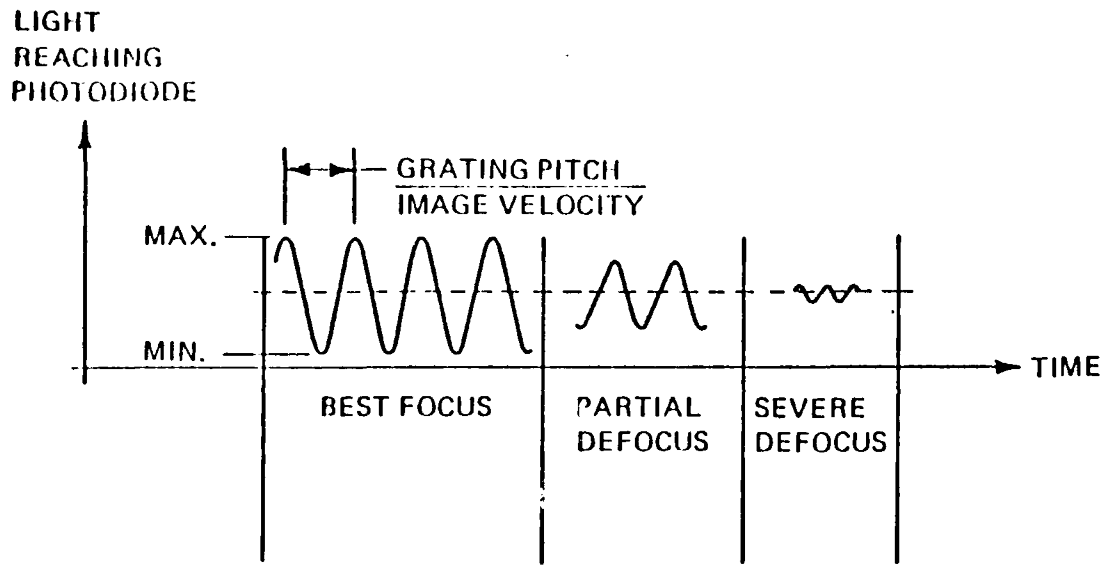
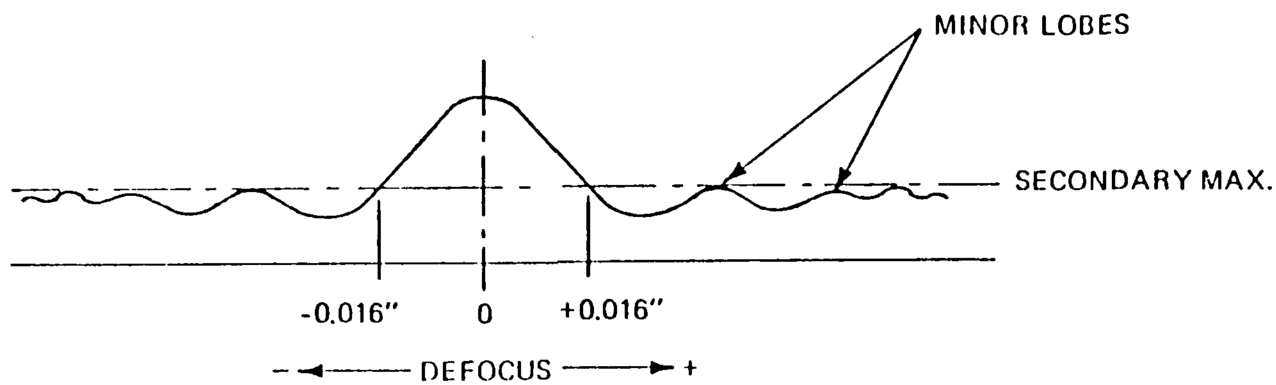


FIGURE 3.1-5. COMPUTER



RELATIONSHIP BETWEEN FOCUS AND INSTANTANEOUS MAXIMA

FIGURE 3.2.4-2



RELATIONSHIP BETWEEN RESPONSE AND DEFOCUS FOR A FIXED GRATING PITCH

FIGURE 3.2.4-3

Vernier Motion is required to locate the best focus position to within ±.001 inches. Vernier correction is accomplished by offsetting the carriage by a minus .010 inches from the acquisition best focus position and driving the carriage at a slow rate. With the scan mirror oscillating, the photodiode is read and stored at .001 inch intervals. After driving through approximately 20 readings, the carriage is returned to the position producing the highest response.

3.2.5 Sensing Head and Video Processor

The sensing head is the assembly which senses the image by means of a CCD detector chip array. Within this head are electronics to ensure proper CCD operation and video amplification. In addition, the sensing head contains exposure circuitry to measure scene brightness and correct for the proper number of TDI integrations.

The processor receives and filters an amplified video signal from the sensing head. Corrections are made to compensate the video signal for beam-sharer fall-off occurring at chip edges, and for photosensitive differences between elements. Background subtraction and video amplification are also performed with the video in a digital form. The data are recorded on an airborne recorder. The processor also communicates with the onboard computer system and controls airborne recorder operation. In addition, the video processor detects IMC and FMC errors and provides correction signals for either the scan or FMC servos.

3.2.5.1 Airborne Video Subsystem

The airborne video subsystem, see Figure 3.2.5-1, consists of an analog/digital processor and a CCD focal plane with drivers, logic, exposure diodes, and exposure control circuits. Also included as part of the airborne video subsystem are the IMC detection circuits for the image-motion-correction servo subsystem.

3.2.5.2 Focal Plane Electronics

The analog and digital processor outputs an end-of-line sync, a 1.45 MHZ clock, and the number-of-integration-select code to the Array Logic Card. This card processes the signal and then feeds proper timing and control signals to the eight Array Driver Boards. The eight Array Driver Boards (6 video and 2 IMC detection) supply the CCD chips with the proper voltages, timing, and number-of-integration codes. The video from the CCD's, is amplified by a factor of ten on the Array Driver Board, and then sent to the Processor Console.

Located on the focal plane are 15 diodes used for exposure control. The ouputs of the 15 diodes are fed to the Auto Exposure Control Circuit. This processes the signal and provides a 0 to -10V. range exposure signal for each diode selected. The diode selected is determined by a computer word received from the Subsystem Interface Card. In addition to storing and supplying the computer word, the Subsystem Interface Card processes the 15 exposure signals as they are selected. The exposure signals are converted to 8 bit digital words and gated to the computer by multiplexer circuitry.

AIRBORNE VIDEO SUBSYSTEM

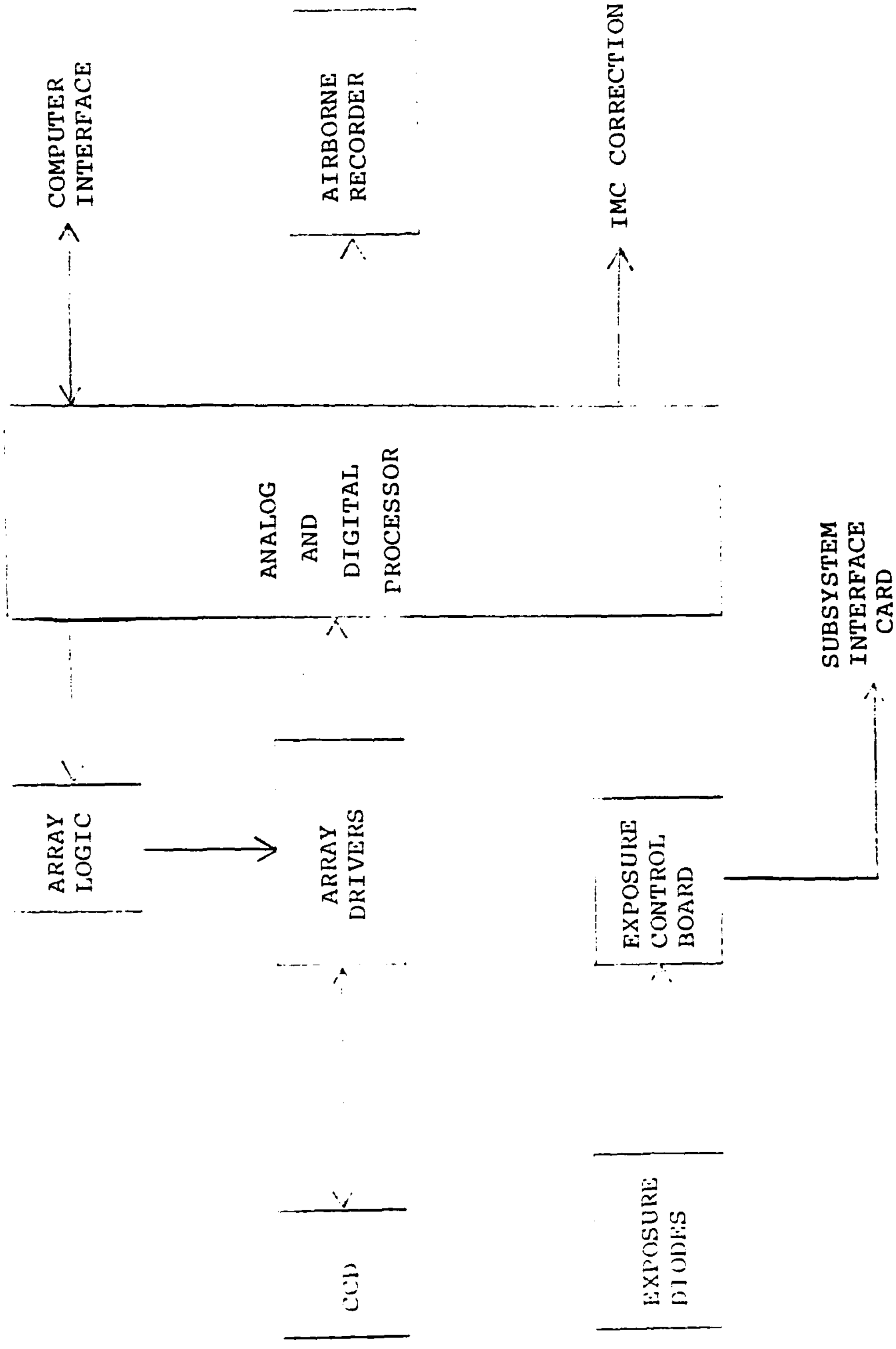


FIGURE 3.2.5-1

3.2.5.3 Processor Electronics (see Figure 3.2.5-2)

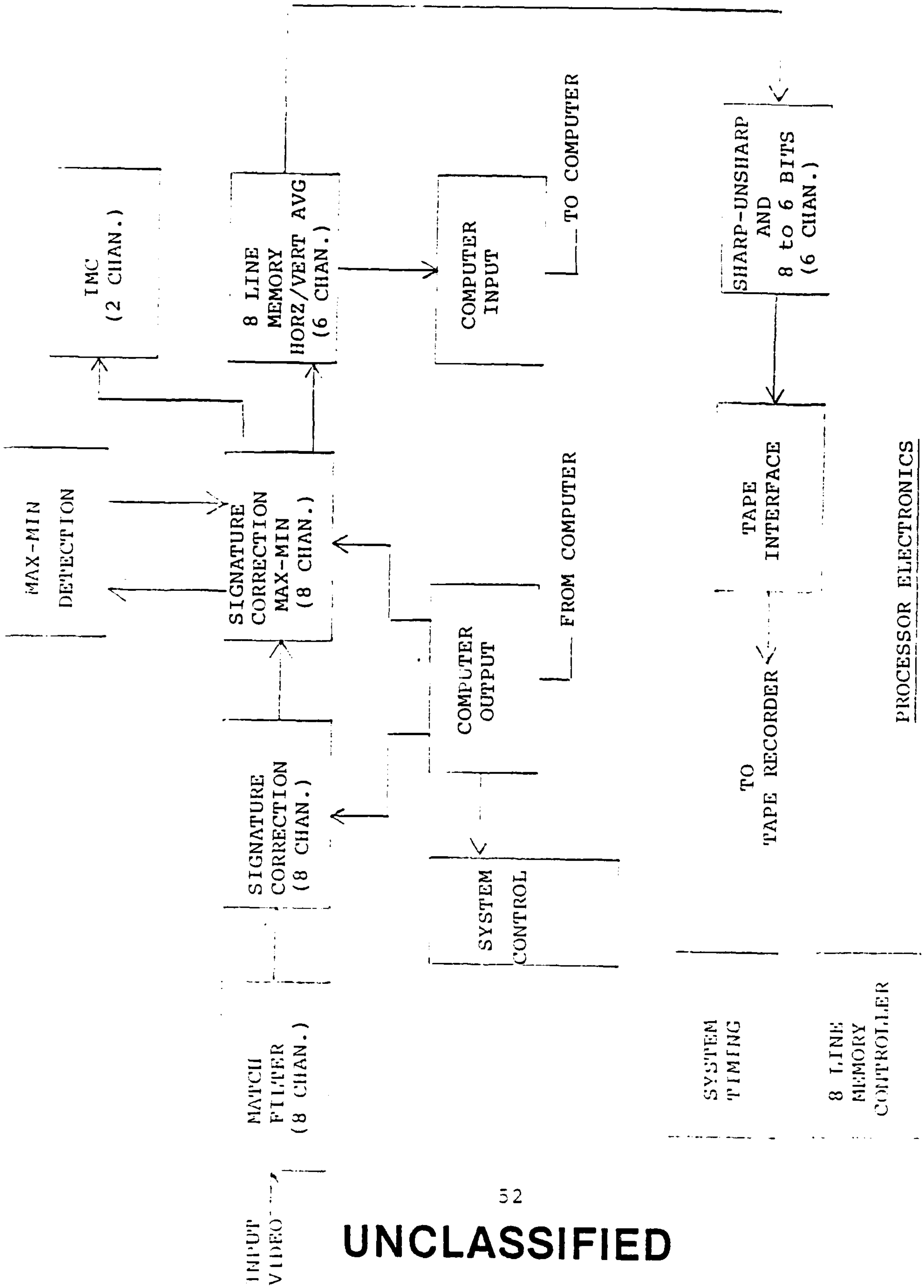
The processor electronics are contained in a three-bucket card rack located in the Processor Console. The processor has both an analog and a digital section. The analog section consists of 8 identical channels. Only one representative channel is described. Two of the channels, processed by the analog section, are fed to the IMC circuits. The other six go to the digital section of the processor. The digital section consists of 6 identical channels. Again, only one channel is described. Circuits common to the channels are described individually.

3.2.5.3.1 Analog Section Of Processor

The amplified Video signal comes to the processor console from the sensing head. Each of the eight channels of video signal goes through a Matched Filter Card, a Signature Correction Card, and a Signature Correction-Max-Min Card. Video from the S.C.M.M. Card also goes to two Max-Min Cards. The six video channels go to one set of two cards and the two IMC channels to a second set of two cards.

3.2.5.3.2 Matched Filter Card

The amplified video signal from the focal plane amplifier is fed into one input of a differential amplifier where it is subtracted from the Sensing head ground signal; effectively cancelling transmission cable noise pickup. An inverted video signal is then fed through a matched filter for switching noise reduction and a two-times amplification.



PROCESSOR ELECTRONICS

FIGURE 3.2.5-2

At the beginning of each image scan line there are a few non-imaging "dark" pixels. This dark level is sampled as an average dark level and stored. The stored level is then subtracted from each of the 1024 sampled-and-held image pixels. At the output amplifier on this card the video gain is reduced by half.

3.2.5.3.3 Signature Correction Card

The video signal goes through three stages of signature correction, two of which are performed on this card. The first is dark-signature correction. Every pixel has a different dark signal level. Prior to sensor operation a dark signal calibration cycle is performed on each CCD chip. A dark signal video line from a "capped" array (i.e.; no light input) is fed through the dark signature circuits (uncorrected) and digitized. These digital data are then sent via the calibrate interface circuit to the computer where they are stored.

During normal imaging operation the stored dark signature is recalled and subtracted pixel-by-pixel from the video signal. Corrected video is then sampled and held in a register.

The second circuit on this card is the beam Sharer correction circuit. The beam Sharer used in the focal plane causes a fall-off of image intensity, due to image beam shear of up to 50% at each end of the image beam. To correct for beam shear the signal is split into two paths which are eventually summed. The first path is a resistive divide with a gain of 0.5. The second path has a gain varied from 0 to 0.5, corresponding to a prestored 7 bit code recalled from an EPROM. The X variable gain values were previously determined and stored from calibration measurements made on the Beam Sharer. The two video signals are resummed, sampled-and-held again and then transmitted from the card.

3.2.5.3.4 Signature Correction Max-Min Card

Light signature correction is the third stage of video signal correction. Each photosensitive cell of the CCD array has a slightly different gain. During preoperation calibration procedures, these differences are measured and stored in the computer. During normal imaging operation the computer recalls the correction factor for each pixel. This correction factor is multiplied with one-half of the corresponding video pixel value, previously split off in a resistive divider. The corrected gain video is then added to the other half of the video signal. After another sample and hold operation and further resistive attenuation the signal is amplified by a factor of five. This procedure corrects for signal loss through the three correction stages and the three sampling stages with a final resultant signal in the range between zero and plus five volts.

Part of the video signal is then directed from the correction Card to the two Max-Min Cards. The remainder after going through a divider has the offset signal from the Max-Min cards subtracted from it. The new signal is doubled in amplitude.

In the final stage before going to the A/D converter, the video is multiplied by the gain signal from the Max-Min Cards. One tenth of the signal, in the 0 to -1.25 volt range is filtered, eliminating random noise and, lastly, divided one more time reducing the maximum signal to -0.5 volts. This signal is then sent to be digitized.

3.2.5.3.5 Max-Min Detection Cards

Detection of the maximum and minimum signal levels in the six video channels is continuously monitored to determine the overall signal spread. These signals are fed to the computer. A similar circuit performs the same signal extreme detection for the two IMC channels on another card.

A second set of detection circuits monitors the maximum and minimum signal levels in each video line. These maxima and minima are used to determine the gain and offset correction signals for the Signal Correction Max-Min Cards. Maximum and minimum levels are measured for each of the six video channels and the two IMC signal channels.

The gain signal is obtained by doubling and polarity inverting the line maximum and adding this to the doubled line minimum. This is the peak-to-peak voltage range. One sixteenth of the range signal is added to the line minimum producing the minimum offset signal. The five volt spread of the peak-to-peak signals is divided into 12.5V to rescale the resultant gain signal.

3.2.5.4 Digital Image Processing

The main functions of the video signal digital processing are to enhance the low contrast imagery using Non-Sharp-Masking techniques and to compress the resultant signal for in-flight digital tape recording storage.

3.2.5.4.1 Image Enhancement

Non-Sharp masking is performed to enhance the high frequency information in the video signal. This processing reduces the background, relatively larger low frequency brightness variations, to permit amplification of the low contrast object details. The Image Enhancement circuit consists of an 8 Line Memory, Vertical Averaging Circuit and a Center Data Minus Unsharp Data circuit. These circuits are described below. The function of the Enhancement circuit is to enhance video transitions from one light level to another. This is performed by taking a running average of an 8 x 8 pixel area and subtracting this value from the center pixel value of that area. This can best be seen by referring to Figure 3.2.5-3.

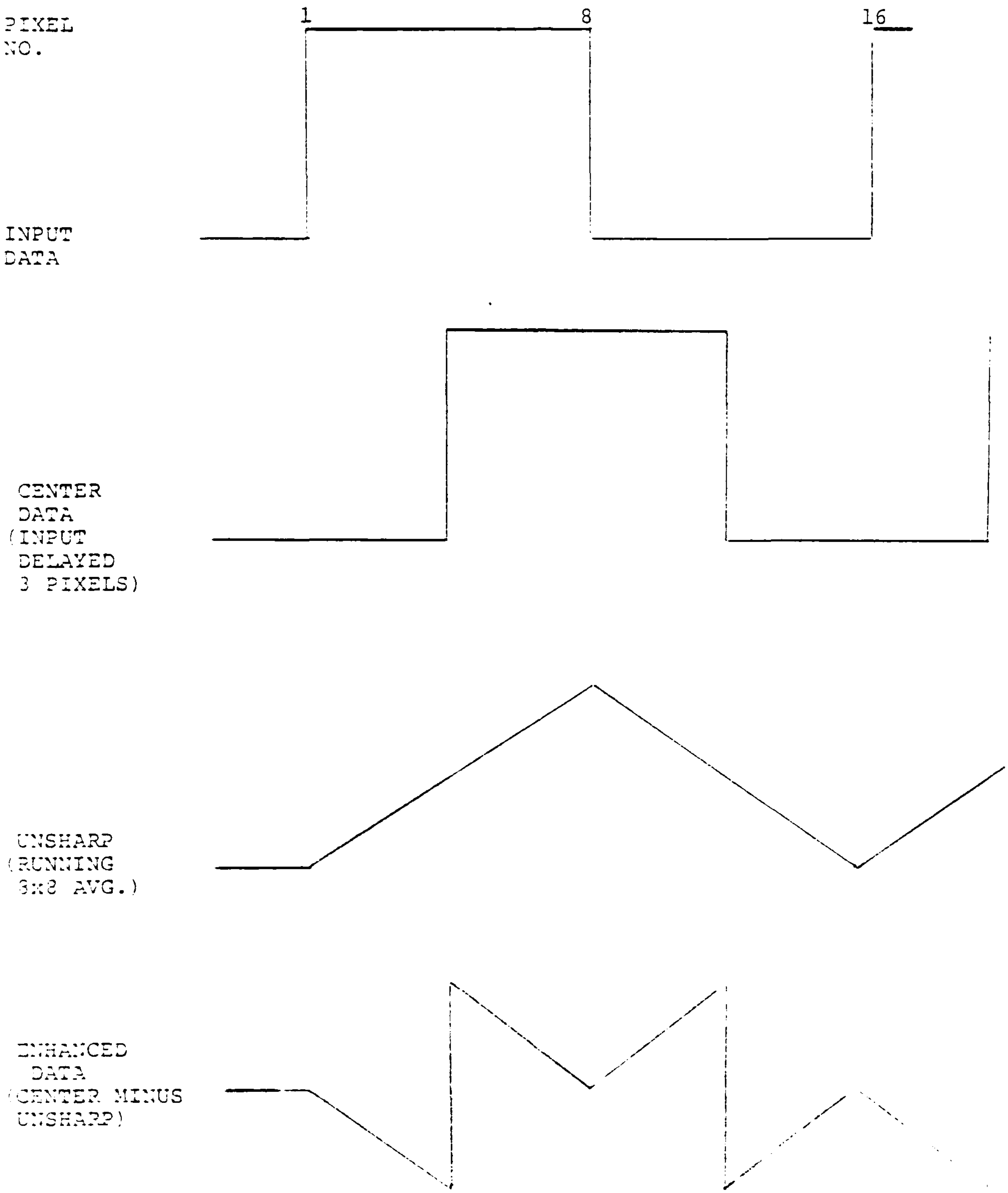


IMAGE ENHANCEMENT ANALOG WAVEFORMS

FIGURE 3.2.5-3

3.2.5.4.2 8 Line Memory - Unsharp Data

To obtain a running average of an 8 x 8 pixel area the eight line memory accumulates a sum of eight contiguous lines. Eight bit words are received from the Max Minus Min Detector Circuit. Eight lines, with 1024 pixels of data per line and each pixel an 8 bit word (65,536 bits) are stored in this Memory section.

$$8 \text{ Lines} \times 1024 \frac{\text{pixels}}{\text{line}} \times 8 \frac{\text{bits}}{\text{pixel}} = 65{,}536 \text{ bits.}$$

These eight line packets are first summed in the vertical direction (in the Vertical Averaging Circuit) as the sum of individual pixel columns. The result, 1024 column sums of eight pixels each are then added in the horizontal direction, to each other as the sum of eight horizontal sequential sums (in the Horizontal Averaging Circuit). The result is a running sum of 8 x 8 matrices. Dividing these Matrix sums by 64 yields an average value for each matrix. The average values of this continuous process is the "UNSHARP" data. Averaging the data in this manner, effectively filters the original data to remove the high frequency components.

3.2.5.4.3 8 Line Memory - Center Data

A second function of the Eight Line Memory is to generate a set of delayed pixel data known as Center data. Center data is obtained by taking data from the memory after a four line plus three pixel delay.

3.2.5.4.4 Vertical Averaging Circuit

The function of the Vertical Averaging circuit is to generate an output that is the running sum of 8 vertical lines. 1024 pixels of line one are added to the respective pixels of lines two through eight. Each line of data is processed in a FIFO mode (first in - first out) after an eight line delay. When the memory is filled with eight lines, the delayed data are summed and stored in a 1024 x 11 memory. (The sum of 8, eight bit words is an eleven bit word.) See Figure 3.2.5-4.

The first line is then read out of the memory and a new eighth line is read in to form a new eight line set. Thus a running eleven bit vertical sum called "VAV" data is formed.

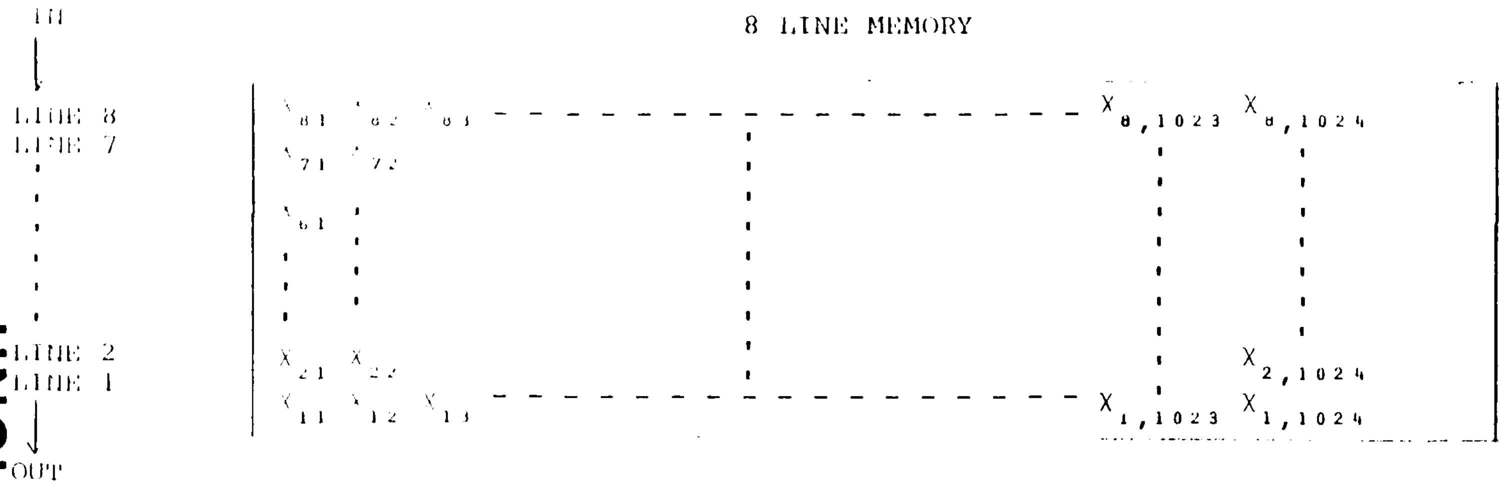
3.2.5.4.5 Horizontal Averaging Circuit

The function of the Horizontal Averaging circuit is to generate an output that is the running sum of eight serial, vertical, pixel sums from within a VAV line (See figure 3.2.5.-5). Each VAV line is closed loop processed through an adder whose output is fed back to its input via a register. As new data, an eleven bit pixel sum, is applied to the adder, the previous VAV pixel sums stored in the register are added to this new data. This continues until a total of 8 pixel sums have been added and stored in the register. While the horizontal pixel sum is being performed each input pixel sum is also stored in a 8 x 11 FIFO memory. When the nineth word and each succeeding word is fed into the adder the register puts out a 14 bit word (the sum of 8 eleven bit words is a 14 bit word). This 14 bit word is simultaneously sent to a subtractor and a divider. In the subtractor a pixel sum from the 11 bit memory is subtracted from the horizontal 14 bit sum and then added to the new adder word thus creating a running sum of an 8 x 8 pixel matrix. In the divider the 14 bit word is divided by 64 computing the average pixel value for the matrix area. This average value is the UNSHARP data.

3.2.5.4.6 Center Data Minus Unsharp Circuit

The function of the CENTERDATA Minus UNSHARP Circuit is to generate an 8 bit word which is an intermediary form of the SHARP data.

8 LINE MEMORY



VAV = Σ LINES 1 THROUGH 8

$$VAV = \sum_{1}^{8} x_1,\ \sum_{1}^{8} x_2,\ \sum_{1}^{8} x_3 \ \text{-----------} \ \sum_{1}^{8} x_{1023},\ \sum_{1}^{8} x_{1024}$$

x = 11 BIT WORD

FIGURE 3.2.5-4

VAV DATA FROM 8 LINE MEMORY

~~(C)~~ Specific experiments demonstrated the ability of integrating detectors to extract information from low contrast scenes. Photo sets 4-1 and 4-2 give two examples of the image signal-to-noise improvement obtained by increasing the number of integrations. Under identical imaging conditions, the picture sets in each figure compare the quality collected imagery for four versus sixteen integrations. All pictures were taken from a slant range of 12NM (depression angle of 16°) between 11:00 and 11:40 a.m. on 6/22/80.

(C) Scene brightness was approximately 800 foot-lamberts. Image contrast was 1.05:1. The 16 integration photos were taken with the TDI-CCD at just less than 50% of saturation (about 300,000 electrons). The exposure time was 12.5 msec. At 4 integrations, the exposure time was 3.1 msec. Collected signal was approximately 75,000 electrons.

~~(C)~~ The samples illustrate clearly that TDI is required to achieve noise free imagery. The top two photos of each figure illustrate low signal levels. An insufficient number of electrons were collected. The signal-to-noise ratio in these photos is about 10:1 between the maximum and minimum brightness areas of the scene. The lower photos in each figure illustrate the increases in utility obtained by being able to collect sufficient signal. The ability to collect and handle large numbers of electrons in small detector sites was one of the trade-off considerations relating resolution and contrast detection during system design. This data indicates that system performance, at low contrast, was clearly limited by signal collection capability and not detector element size.

(U) Removal of haze levels in the image using an analog signal processor with minimum/maximum detection and background subtraction.

(U) Development of an image enhancement algorithm which processed digital scene data to enhance edges and further remove slowly varying background. This algorithm served a dual function of image enhancement and data compression by compressing image data from 8 to 6 bits.

(U) Digitization and storage of data in an airborne recorder for subsequent playback in a ground station.

(U) Development of a ground station for image playback, reconstruction and reproduction. This station included a digital playback deck, a digital/analog data reconstruction unit and a laser beam recorder for image reproduction and processing on five-inch dry silver film.

(U) Once fabricated, this system was installed in a C141 aircraft and flight tested. The installation included modification of the aircraft to replace the crew entrance door with a 29 inch diameter optical window. Flight tests totaled 73 hours in 23 separate flights.

(U) 4.3 TEST RESULTS SUMMARY

[redacted] Flight tests of LOREORS demonstrated the ability of silicon based TDI-CCD detectors to double the effective working range of a conventional film reconnaissance camera in moderate and heavy haze. Identification of aircraft was achieved at 30NM slant range with moderate haze producing an image contrast of 1.006:1. Identification of vehicles was achieved from 12NM at an image contrast of 1.02:1. Both contrast levels were substantially below the limit of a film camera (1.1:1). See sample photos sets 4-1 and 4-2.

(U) Development of a new, large format (1024 x 64), silicon, TDI-CCD detector array which was required to improve the signal-to-noise ratio of the collected image data.

~~(C)~~ Development of an assembly technique for optically butting together many CCD detectors into a single long array with as many as 18,000 pixels, with subsequent fabrication of a 6000 pixel (six chip) array for use in the camera system.

~~(C)~~ Design and fabrication of an f/12, 144 inch focal length lens optimized for MTF over the entire silicon response band (4500 to 9500A°) to the edge of its field. The lens provided a wide, 5.7 degree, field-of-view plus a telephoto ratio of 1.5 for compactness.

(U) Development of a sensitive temperature stabilization system using thermocouples strategically placed throughout the lens barrel and air circulation system. This system was designed to stabilize camera temperature to within one degree of ambient for any ambient between 55°F and 80°F.

(U) Development of an auto focus system which optimized infinity camera focus, over the silicon spectrum, for any combination of pressure and temperature. The pressure range varied from ground level to 10K feet. Temperature from 55°F to 80°F.

(U) Development of a system for automatic camera pointing based on inertial navigation data. This system performed computer calculations based on aircraft latitude, longitude and altitude plus camera pitch, roll and yaw to determine the correct pointing angle of the camera scan mirror for target acquisition. Up to two hundred target locations, in latitude,longitude and altitude, could be entered into the mission memory.

(U) 4.0 SUMMARY OF TASKS AND RESULTS

(U) 4.1 INTRODUCTION

~~(C)~~ The objective of the LOREORS program was demonstration of the performance capability and performance limits of charge coupled device detectors, operating in the visible to near infrared spectrum, for long range reconnaissance. Adequate demonstration of this capability required the fabrication of a flyable brassboard camera system and its subsequent test. To this end, the tasks outlined in the following paragraphs were performed. In total, they formed a substantial effort designed to verify the ability of these detectors to provide useful intelligence data, under heavy haze conditions, out to a slant range of 30 miles.

~~(C)~~ These requirements were translated, on a theoretical basis, into a set of performance goals for the LOREORS system. The theoretical goals included:

- o Operation between brightly illuminated and cloud shadowed targets.
- o Demonstration of one foot GRD, with 30 mile slant range, from 30K feet, with an image contrast of 1.00125:1.

(U) In order to demonstrate this remarkable capability, the following subtasks were identified and performed.

(U) 4.2 TASKS INCLUDED:

(U) Development of a side oblique camera system (designed to operate from a medium to high altitude platform) from which imaging data was collected in a sector scan panoramic mode.

complete image is composed of 12 800 lines. The LBR converts these data to a hardcopy image by writing with the coherent light beam on a dry-processed silver film. Annotation data for the scene are included as part of the digital data processed thru the Data Processor to the LBR for inclusion on the final image display.

and can be examined by the operator from the DATA inquiry program while "SCANR" is running.

"SCANR" will automatically start & stop the video tape recorder when required. It will initiate the program GTEXP to perform the exposure determination and the CCD calibration data transfer at approximately 5 seconds before the start of picture taking. "SCANR" also starts and stops the picture scan and the data logging during picture scan. After all the targets have been processed, LOREO will terminate "SCANR".

3.2.7 Ground Station Image Reconstruction

Reconstruction of the airborne tape recorded stored image was accomplished in the Ground Station which is equipped with a Playback Tape Deck, a Data Processor and a Laser Beam Recorder. Replaying the digitized data from the tape player into the Data Processor, the original image was reformed by recombining the high and low spatial frequency components of the image data.

Each unsharp 8x8 matrix average of original data (low frequency data) is multiplied by a interpolation factor to remove processing noise. Further low frequency filtering is performed by computing the average of 4 adjacent 8x8 element areas and using these new average values as updated unsharp data. This reformed unsharp data is then added to the sharp data to obtain an edge enhanced, compressed range scenic reproduction.

Processing is performed simultaneously, in parallel on each of six data sets. This final image data is then placed in a buffer memory until recalled for readout.

During readout the laser beam recorder requires 8-bit parallel words from the Data Processor. The six sets of data are read out serially to the LBR as six 1024, 8-bit words per image line. A

Similarly to remove power from the system a "DOWN" command must be keyed in. A list of devices to be deenergized will be listed with a procedure. Execution of a space and carriage return combination indicates an end of the power down subroutine.

3.2.6.3 Sensor Computer Control

A MISSION command is used to start the imaging control program called "SCANR". This "SCANR" program, which will run concurrent with the "LOREO" program, enables the presighting of targets imaging, and target processing. I/O data is also entered into the system common memory on a regular basis for later retrieval. After a series of preliminary initializing TDI program questions, which must be answered by the operator before proceeding, the system will be placed in "SCANR"; an automatic program for controlling the Sensor movements for pointing and image scanning. Target parameters will be automatically acquired from the various system memory sections and pointing angles computed. The Sensor FMC & Scan gimbals will be driven to the desired orientation with respect to the present aircraft location and altitude.

Program "SCANR" schedules itself every 40 msec, each time executing one cycle consisting of; 1) reading navigation data from the INS system, 2) reading encoder positions, 3) calculating desired servo positions or rates, and 4) transmitting servo drive commands to point the Sensor at the target or to perform an image scan. At the conclusion of each image scan, the program acquires the next target and repeats the process until all targets have been completed. When "SCANR" is in the pointing mode, the servos are positioned to the calculated angles. When "SCANR" is in the scanning (image acquisition) mode, rate equations are solved to determine the FMC & SCAN rates. These angles or rates are converted to servo output commands and sent to the FMC & SCAN servos.

The INS system, NAV data, encoder positions, altimeter readings and the IRIG TIME values are stored in common memory by "SCANR"

INVALID COMMAND: TYPE "HELP" FOR COMMAND LIST

The "LOREO" program is self instructional and is organized to assist the uninitiated user with the assumption that the user understands the system operation. A "HELP" input produces the Command Summary on the CRT screen. The operator may terminate this "LOREO" program at any time by executing an exit command, /E; this returns the computer to the operating program.

A set of safety interlocks have been programmed in "LOREO" to protect the system from Sensor damage by improper or conflicting I/O instructions. These interlocks are stored in the system common memory section and are unaffected by exits or re-entries into the LOREO programs. Interlock status can be examined by issuing a "STATU" command through the keyboard; interlock flag status will be displayed on the CRT monitor. The five status flags are: System Power Up, Mirror Caged, Mission In Progress, Logging On and Recorder On. A simple "Yes" or "No" statement is displayed as the status report. The compressor air status and the current target number in process are also displayed. Interlock flag status information is important because certain system commands will not be executed unless the flags are properly set. Table 3.2.6-2 outlines the command interlock combinations required for given commands.

To apply power to the Sensor system the operator uses the "UP" command. This produces an operator checklist and sequence of procedures instructing the user how to apply power to the equipment. Upon completion of this sequence, the operator must type in a space and a carriage return on the keyboard. The air compressor status will then be checked. If the air status is faulty, a fault message will be displayed and the sequence will be stopped; otherwise this program routine ends and returns to the main LOREO program.

I/O interrupt processing priority is allocated by device speed or urgency need. Highest priority is given to the Time Base Generator (the system clock). The three general interfaces are at the next level; the Servo/Navigational, Autofocus/Exposure/Time and Video Processor. The ssytem disc has the next lower priority followed by the system, CRT console, the data logger and finally the line printer.

3.2.6.1 Memory Assignment

Memory mapping for all software programs is performed with HP's RTE-III (Real Time Executive) system. The computer can address only 32 pages of memory at one time. The LOREORS system has 64 pages of memory which are subdivided into a common memory, accessable to all programs, a resident memory, only for the computer and a System Available Memory (SAM), only for LOREORS systems programs.

3.2.6.2 Command Program

Access to the LOREORS sensor System is provided with a program labled "LOREO". To operate the Sensor the user types-

*RU, LOREO

on the CRT console keyboard. An operator response is then requested by the program with a prompting statement appearing on the CRT screen, such as-

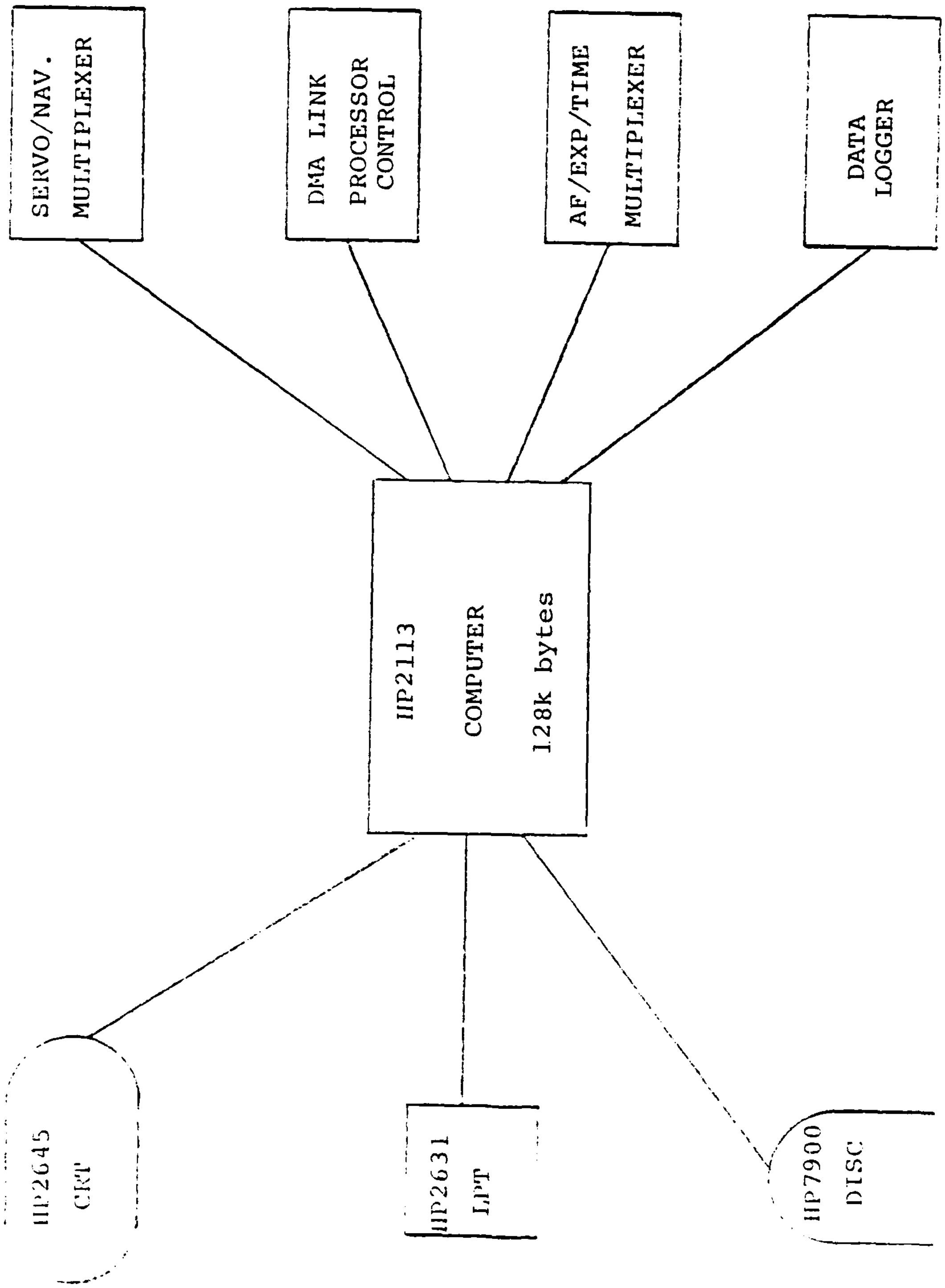
SYSTEM COMMAND?

Acceptable operator responses are listed in table 3.2.6-2, Command Summary Table. The complete command word may be typed in, however, the computer responds only to the first two characters. When an illegal command (not included in the command set) is keyed in it will not be recognized and the following error message will be displayed:

Command	Power-On	Mirror Caged	Mission in Progress
DOWN	yes	yes	no
UP	no	-	no
CALIBRATE	yes	no	no
AIR	-	-	-
TARGETS	-	-	-
FOCUS	yes	no	no
SERVOS	yes	no	no
DATA	-	-	-
MISSION	yes	no	no
ABORT	-	-	yes
UNCAGE	yes	no	no
FIX	yes	no	no

TABLE 3.2.6-2

COMMAND INTERLOCKS



LOREORS SYSTEM BLOCK DIAGRAM

FIGURE 3.2.6-1

INPUT 8 BIT	=	OUTPUT 6 BIT	INPUT 8 BIT	=	OUTPUT 6 BIT
0-11		0	129		33
12-32		1	130		34
33-48		2	131		35
49-60		3	132		36
59-69		4	133		37
70-76		5	134		38
77-82		6	135		39
83-87		7	136		40
88-91		8	137		41
92-95		9	138		42
96-98		10	139		43
99-101		11	140		44
102-104		12	141		45
105-106		13	142		46
107-108		14	143		47
109-110		15	144-145		48
111-112		16	146-147		49
113		17	148-149		50
114		18	150-151		51
115		19	152-154		52
116		20	155-157		53
117		21	158-160		54
118		22	161-164		55
119		23	165-168		56
120		24	169-173		57
121		25	174-179		58
122		26	180-186		59
123		27	187-195		60
124		28	196-207		61
125		29	208-223		62
126		30	224-255		63
127		31			
128		32			

TABLE 3.2.5-6

8 TO 6 BIT COMPRESSION

As the title implies the UNSHARP data are subtracted from the CENTERDATA which tends to emphasize video level changes or enhance high frequency data. These new data, labled "SHMUNS" data, are transferred to an 8 to 6 bit Converter circuit.

3.2.5.4.7 8 to 6 Bit Converter

The function of the 8 to 6 BIT CONVERTER is to compress the 8 bit SHMUNS data to 6 bits. This compression is necessary because the capacity of the tape recorder is limited to 6 bits per pixel. This function is performed with a 256 x 6 PROM programmed as per Table 3.2.5.-6 below. The 8 bit SHMUNS data are used as the address for the PROM. The 6 bit output (herein referred to as SHARP) of the PROM is formatted and then recorded on three adjacent channels of the tape recorder. This SHARP signal, and the UNSHARP signal recorded on channel 19, are used by the ground station to reconstruct the airborne picture.

3.2.6 <u>Computer Subsystem</u>

Control of the LOREORS System has been totally automated and programmed for operation under computer Control. The LOREORS Computer Subsystem consists of an HP 1000 minicomputer utilizing an HP 7900, 5 megabyte disc. (This disc was selected because of its prior history of usage in the aircraft.) Supporting peripheral equipment consists of an HP 2645 CRT terminal with cassette drives, an HP 2631 line printer and several interface configurations for the multiplexers and processors in the sensor equipment. One universal interface is used to multiplex servo and navigational inputs, a second multiplexes autofocus, exposure and time data and a third interfaces the video processor over a DMA link. A breadboard interface is used to monitor the air compressor operation. A Fluke Data Logger, which scans the Sensor thermocouples, uses an RS-232C link via an asynchronous interface. See figure 3.2.6-1.

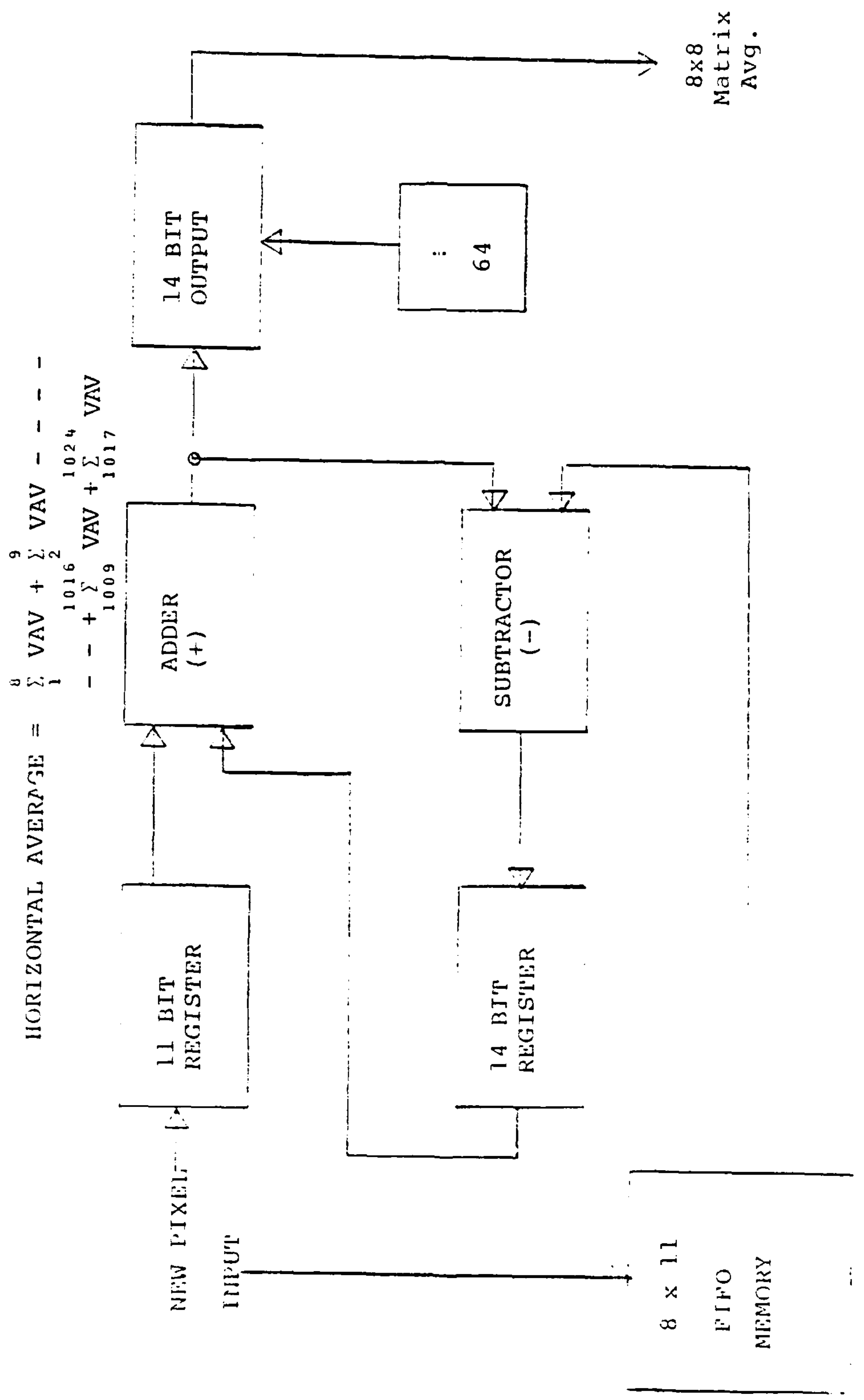


FIGURE 3.2.5-5
UNSHARP DATA

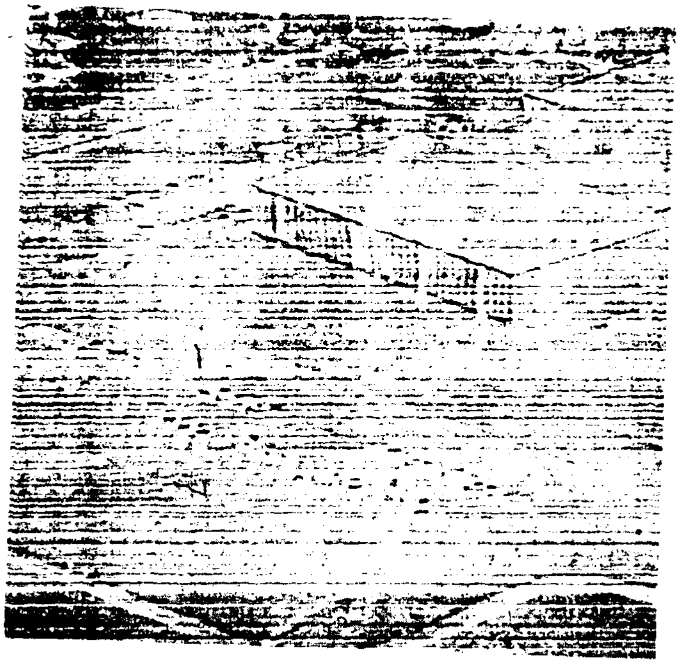
UNCLASSIFIED

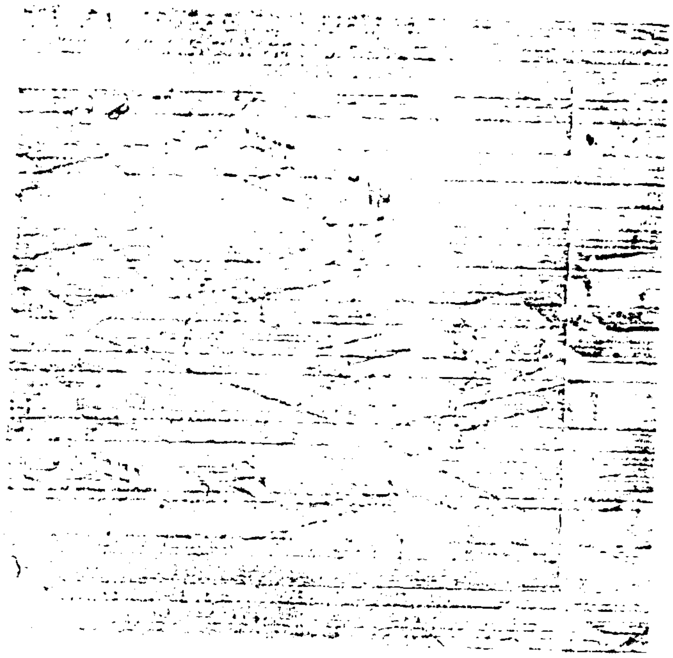
[redacted] The photo shown in photo sets 4-1 and 4-2 also help to illustrate the pointing accuracy achieved by the LOREORS system under inertial control.

[redacted] The four versus sixteen integration pictures were taken approximately 40 minutes apart. In each case, the test aircraft had flown an octagonal route which required 40 minutes to complete. On successive passes, the overall pointing accuracy to the middle of a frame of imagery was 300 feet at 15NM. This error is primarily accounted for by drift in the inertial navigation unit on the aircraft.

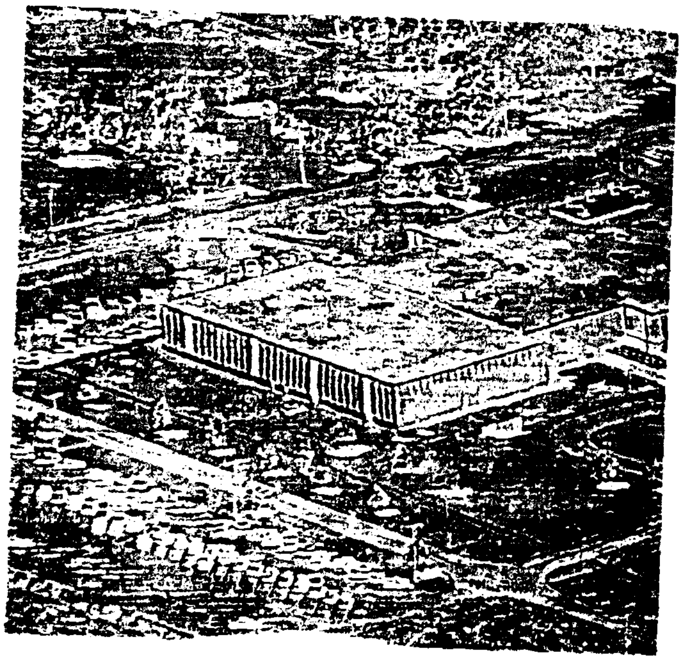
[redacted] The advantage of TDI detectors in obtaining intelligence information where film or single-line linear array CCD detectors could not was demonstrated in the preceding test results summary.

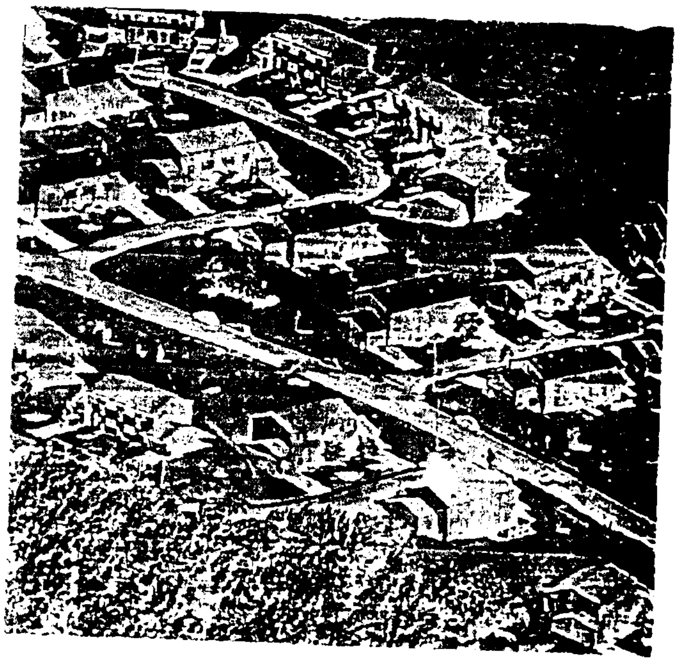
[redacted] The introduction of the TDI concept enables data collection to long ranges, where atmospheric haze would normally create a barrier. The integrating capability however, increases the camera sensitivity to uncompensated motion. Maximum integration time for the LOREORS system, using 64 integrations, was 50 milli-seconds. Most imagery, taken within two hours of noon, required 16 integrations to produce half-saturation in the CCD detector wells (500,000 electrons). At this level, the camera exposure time was 1/80 second. This is about twelve times longer than a film system. At the limiting (NYQUIST) resolution of LOREORS, 11 micro radians per line pair, uncompensated motions would have to be kept below 440 micro-radians per second in order to insure that MTF at the limiting frequency would not be reduced by more than 64%. This is about one third of the level achieved in a good long focal length film camera. Operation at 64 integrations would require stabilization still four times better.





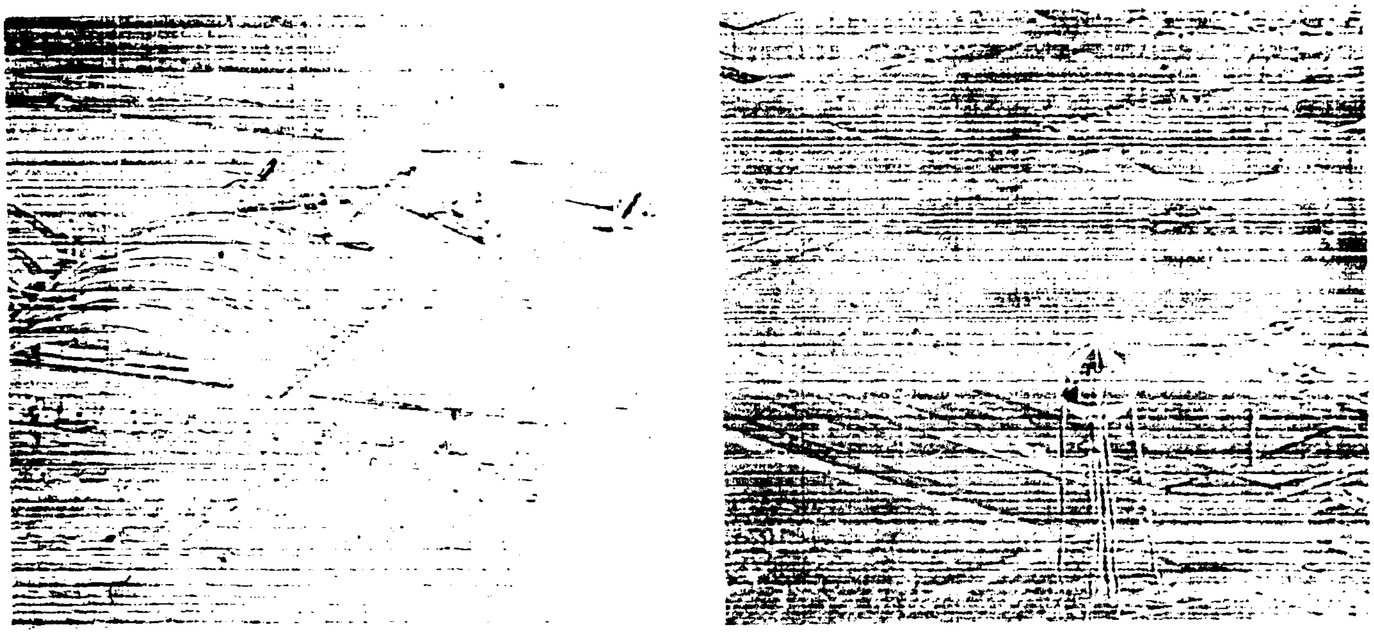
FOUR TDI INTEGRATIONS



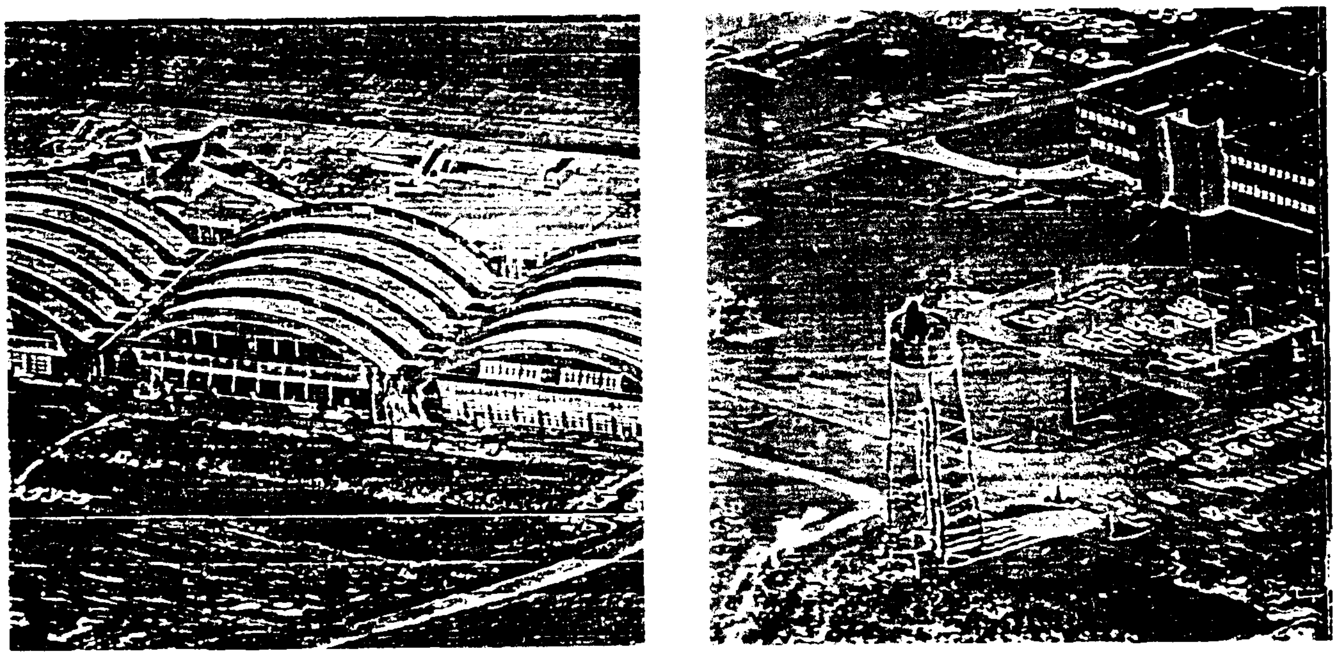


SIXTEEN TDI INTEGRATIONS

PHOTO SET 4 1



FOUR TDI INTEGRATIONS



SIXTEEN TDI INTEGRATION

PHOTO SET 4-2

~~(C)~~ This fact was realized during the design and fabrication of LOREORS and provision was made for the best gyro stabilization possible in three axes. By calculation of gyro errors, this capability would still fall short of that required for 16, 32, or 64 integrations. For this reason, a novel method of stabilization was developed for use with LOREORS. In this system, residual motion errors were detected using the focal plane image itself. TDI detectors offset by one sample line were placed in the camera. Algorithms were developed which could sense image motion in two directions based on the output from these detectors. This signal was to be added as a correction factor to the roll, pitch and yaw compensation servos. This concept was developed and proven in the laboratory and built into the LOREORS system. Due to time and budget constraints, however, proper test and activation of the system could not be performed during the course of the program. For this reason, resolution in the camera was limited by the stabilization.

(U) 4.4 CONCLUSIONS

The utility of TDI detectors for extracting intelligence information at long slant ranges was readily proven by LOREORS. The resolution limitation of the system was shown to be determined by the degree of camera stabilization achieved. Operational variants of this system can be improved by introduction of the electronic stabilization technique and decreasing the camera f number as much as practical.

APPENDIX A

TECHNICAL REPRINTS

All of Appendix A is unclassified

UNCLASSIFIED

P-77

A Large TDI Focal Plane Assembly with an Optically Contiguous Pixel Format

Henry Sadowski and William Dugger

Paper Presented at the SPIE Los Angeles Technical Symposium
February 4-7, 1980, North Hollywood, California.

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UNCLASSIFIED

A large TDI focal plane assembly with an optically contiguous pixel format

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Abstract

A 6144 X 64 pixel focal plane assembly has been constructed incorporating six 1024 X 64 Time Delay and Integration Charge-Coupled Devices (TDI CCDs) in a beam-sharer configuration. The beam-sharer approaches 100 percent efficiency over the format, compared to a maximum 50 percent efficiency for a conventional beam-splitter configuration.

The TDI CCDs have 20 X 20 micrometer pixels. The focal plane assembly is constructed so that the pixels are contiguous at the optical "butt" between chips to within 2 micrometers and straight within a 6 micrometer error band over the entire six chip length.

These dimensional accuracies were achieved using a precision alignment apparatus developed for this purpose. In a way similar to a comparator microscope, its optical system provides simultaneous overlapping fields of view; one incorporates fixed reference lines while the other contains a view of the CCD chips. A mechanical micro-manipulator is used to provide precise control of chip motion in three degrees of freedom (x, y, ϑ) for each of the two CCD mounting planes.

The modular focal plane assembly technique makes practical the fabrication of large-format, gapless configurations of high optical efficiency. Both the assembly technique and methodology of subsequent repair (replacement of chips after some period of service, should that ever be required) are described in detail.

Introduction

Electro-optic imaging using charge-coupled devices (CCD) is finding increased application to long range aerial reconnaissance systems.[1] The CCD has a greater dynamic range than film which, when coupled with electronic video processing, permits contrast enhancement and subsequent image rendition well beyond the capabilities of film. High sensitivity of the CCD in the near infrared spectral region provides haze-penetration as well. Moreover, imagery can be obtained in essentially real time at remote ground stations through telemetry. Time delay and integration (TDI) techniques permit the application of CCD sensor systems to low light level scenarios.[2]

Current CCD fabrication techniques impose practical limits on the number of photo-elements (pixels) that a single monolithic device may have. This limitation derives from the "yield" of the manufacturing process. While large silicon wafers can be fabricated, the yield of satisfactory CCDs from these wafers becomes vanishingly small as the length and/or area of the individual CCD increases.

The TDI CCD used in the fabrication of this focal plane has 1024 pixels, each 20 X 20 micrometers.[3] Reconnaissance systems require many times this number of pixels; these requirements can only be met by assembling many devices into a focal plane that approaches the equivalent of a single large monolithic CCD.

The beam-sharer focal plane

Several techniques exist for assembling a series of linear CCD arrays into a focal plane to form an effectively contiguous line of photo-elements. These techniques may be categorized as mechanical, electronic or optical butting.

In mechanical butting, the CCDs are placed physically next to each other, end to end, on a common plane. To accomplish this each CCD must have near perfect, active pixels at its extreme ends. The current state-of-the-art in CCD fabrication is not capable of producing such CCDs. Thus, a mechanically butted focal plane will have two or more defective or missing pixels at each butt.

In the case of electronic butting, the CCDs are mounted on a focal plane in staggered bilinear rows with the end pixels aligned but displaced in the direction of image motion. The second row "fills the gaps" in the first row, provided enough electronic delay is available in the form of memory. This memory requirement can be quite substantial, amounting to perhaps 200 or more lines of data. Furthermore, the effective pixel contiguity may be affected by image motion and/or distortion which may occur during the delay time. This is a consequence of the fact that each row is not optically contiguous.

One common optical technique for achieving contiguous pixel focal planes is the use of a beam-splitter, but, this forces one to throw away more than half of the light. However, for optical systems with relatively modest numerical aperture, a beam-sharer can be used which utilizes virtually 98 percent of the light. The beam-sharer focal plane is shown in Figure 1. Its construction is similar to a beam-splitter except that the usual partially reflective/transmissive coating is replaced by alternating fully reflective and transmissive surfaces. Thus, the beam-sharer conserves nearly all of the light.

The CCDs are cemented to the output faces of the beam-sharer (as in a beam-splitter) with the last and first pixel of successive CCDs optically butted to form a contiguous pixel focal plane. However, there is an additional mounting requirement. The pixel boundaries between successive CCDs must nominally lineup with the corresponding boundaries of the reflective and transmissive surfaces.

The width of each reflective transmissive surface is nominally equal to the active photo-length of each CCD. This dimension is modified slightly by the location of the exit pupil of the objective lens, the nature of the optical system and the beam-sharer's material and dimensions. Proper alignment is achieved when the reflective/transmissive surface boundary lies on the chief ray which reaches the corresponding boundary between successive CCDs.

Boundary effects in the beam-sharer

As shown in Figure 2, the beam which falls on the boundary of the reflective and transmissive surfaces is physically divided or "split". The figure illustrates a beam which is centered on the juncture resulting in 50 percent transmitted and 50 percent reflected light. Consider what happens when a beam of light, initially in the fully transmissive region, moves across the reflective boundary. Starting at 100 percent, the transmitted component begins to diminish as the reflected component increases from zero. The number of pixels affected by the boundary depends on the dimensions of the beam-sharer assembly, the beam-sharer's refractive index and the relative aperture or F number of the objective lens.

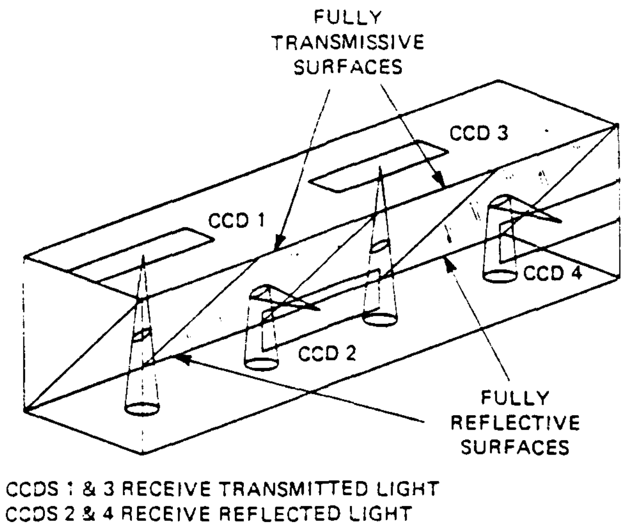


Figure 1. Beam-sharing focal plane arrangement.

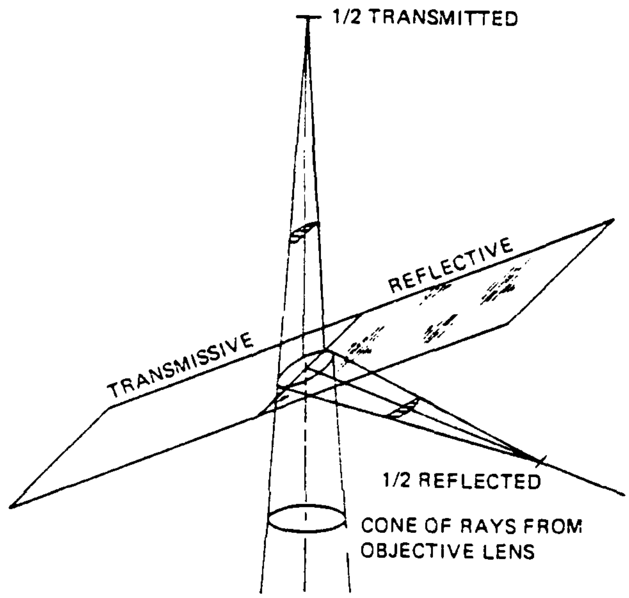


Figure 2. Beam-sharer boundary effects

Figure 3 shows the "shading" or relative illumination on each CCD in the focal plane which results from the boundary effect for the subject beam-sharer. This beam-sharer was designed for an F/12 objective. Its cross section was one inch by one inch made of ZKN-7 glass, with the CCD image plane 0.085" from the surface of the beam-sharer. It can be seen in the figure that only 24 pixels at each end of a 1024 element line are affected at all.

There are two ways of dealing with this "shading". One way is to overlap the CCDs by 24 pixels on each side of the boundary and electronically sum the output video for corresponding reflected and transmitted pixel pairs. This would be equivalent to conserving all of the light with only a slight increase in electronic noise and a slight loss of MTF for the pixels near the boundary. The other way of dealing with the boundary effect is to accept the light loss at the boundary and correct the shading by electronic means.

It is the latter technique which was utilized since electronic correction of the CCD dark signature and photo-response non-uniformity was also implemented. The relative illumination can be no worse than 50 percent at the boundary pixels which means the signal limited noise ratio is reduced by the $\sqrt{2}$ at the boundary. There is a small loss in MTF along the CCD axis for the pixels in the boundary region arising from the division of the effective aperture.

TDI CCD imager

The CCD used in this focal plane has 20 X 20 micrometer pixels and is nominally 1024 pixels long with up to 64 steps of integration. Actually, as seen in Figure 4, the active length is 1030 pixels with 4-1/2 opaqued pixels added at each end. The opaqued pixels serve as a dark reference for DC restoration. They are located at both ends because the output transfer register can be clocked in either direction.

The bi-directional transfer register with a resettable floating gate amplifier at each end permits the same CCD to be used in reflection or transmission. The CCD that sees reflected light must be rotated 180° in its own plane relative to the CCD in transmission. This must be done so that the TDI direction coincides with the direction of image motion as seen through the reflecting surface. Furthermore, to prevent a left for right reversal in the output video, the transfer register of the reflected CCD must be clocked in a direction opposite to that of the transmitted CCD.

The reason for 1030 active pixels is to provide 3 additional pixels at each end of the 1024 imaging pixels. This avoids abrupt end effects and assures uniform crosstalk at both ends. Figure 4 also shows a pair of fiducial marks which are deposited during first metallization to define the 1024 image pixels. The fiducials are required because the channel barriers were ion implanted and the pixels themselves are not visible.

The number of integrations can be controlled by means of exposure control taps. These taps permit 1, 4, 8, 16, 32 or 64 integrations.

Optics for focal plane alignment

The philosophy underlying the alignment of the CCDs in the focal plane was to bring adjacent fiducials on the CCDs into registration with each other and keep all the fiducials in a straight line by optical comparison to a master reference line. Figure 5 shows the optical system used to accomplish this task. The beam-sharer and a datum scale containing the master reference line are mounted parallel to each other on a sliding index plate. This plate is arranged to slide on a flat work table. Successive CCD positions on beam-sharer are indexed over vertical or horizontal fine motion mechanisms (micro-manipulators) used to align the CCDs. The vertical mechanism mounts the transmission CCD on the bottom of the beam-sharer through access holes in the indexing plate; similarly, the horizontal mechanism mounts the reflection CCD on the side of the beam-sharer.

As seen in Figure 5 two microscopes are arranged such that magnified images of the datum scale and the CCD can be viewed simultaneously overlaid on one another. The illumination of each channel can be separately controlled so that, one channel at a time can be viewed, both channels simultaneously or each channel alternately in rapid succession. For example, when doing the alignment of the CCD butt, only the CCD channel is illuminated. However, when the CCDs are aligned for straightness both the datum scale and CCD channels must be illuminated.

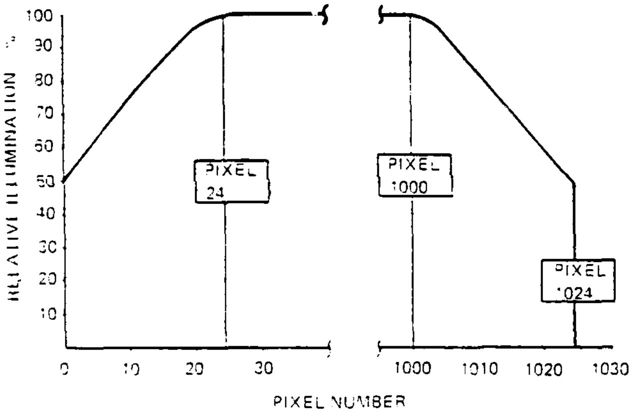


Figure 3. Relative illumination as a function of pixel number.

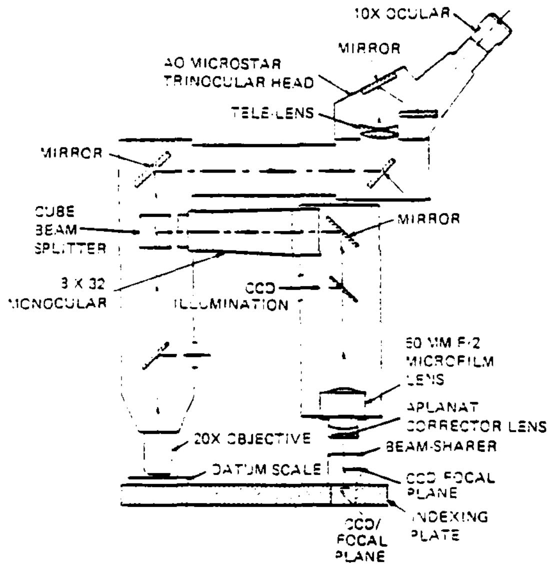


Figure 5. Optical schematic of dual field microscope.

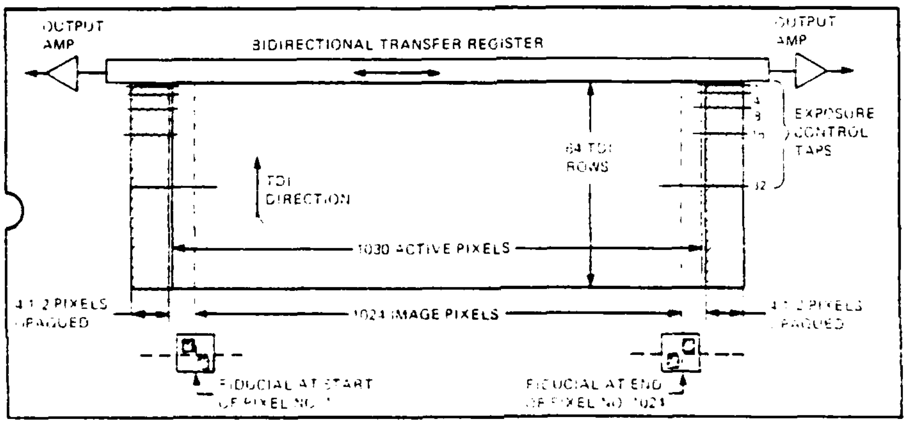


Figure 4. 1024 X 64 TDI CCD imager.

The datum scale microscope is essentially equivalent to the American Optical Microstar® microscope. This type of microscope was designed as a teaching microscope system. It offers the flexibility of easily manipulating the optical length and system configurations without changing the magnification or requiring relays. The flexibility of the system stems from the fact that the objective in this microscope works with an infinite conjugate. Thus, the tube length does not affect the magnification as in a conventional microscope. An A-O Microstar® trinocular head is used with 10X oculars. This head has a Telelens which makes the head equivalent to a telescope with approximately 7X power.

For the datum scale channel, a 20X objective was chosen resulting in a 200 power magnification. There is a beam-splitter above the objective which serves to introduce illumination to the datum scale. Further along the optical path is a cube-type beam-splitter which combines this optical path with that from the CCD focal plane. The remaining path is a series of mirror folds that permit the A-O head to be mounted at a location convenient for the operator.

The CCD microscope channel required a different design. Since the beam-sharer was one inch thick, a long working distance objective is necessary in conjunction with a high system magnification. A further requirement is that the numerical aperture of the objective must be high enough to preserve resolution. The objective chosen for this channel combined a 50mm F 2 microfilm lens with a custom design aplanatic corrector lens.

The aplanatic corrector was made of a low index, low dispersion glass and was designed to correct the aberrations associated with the one inch thick ZKN-7 beam-sharer (primarily spherical, coma and longitudinal color) as well as residual aberrations of the microfilm lens. Supplemental magnification was provided by means of the 8 X 32 monocular telescope adjusted for infinity focus.

The overall magnification in the CCD channel is about 280 which is higher than that of the datum scale channel. This difference in magnification posed no problem in alignment. Focus on the datum scale is accomplished by moving the entire microscope assembly on a vertical slide to which the assembly is mounted. Once focus is achieved, the assembly is locked in place. An independent focus control was provided for the CCD channel objective with sufficient range to focus on the reflective/transmissive boundary anywhere in the prism. The focus motion uniformity and perpendicularity was held within 1 micrometer for the 35 millimeter focusing range. This accuracy was required to position the edge of the first CCD being mounted under the beam-sharer's middle reflective/transmissive boundary as outlined in the focal plane assembly procedure.

Mechanical features of the alignment apparatus

The table which holds the fine motion mechanisms, datum scale and beam-sharer mounting plate is itself mounted to the platform of a precision grinding machine. This platform provides gross motion in X and Y coordinates such that orthogonality and planarity are within 0.0002" in 12". The dual field comparison microscope is mounted on the vertical slide in place of the normal grinding spindle. Thus, microscope focus is accomplished in the Z coordinate with similar orthogonality. An indexed mounting plate on the table surface contains positioning blocks and holding clamps for both the datum scale and beam-sharer. Eccentric cams are provided to adjust the datum scale into parallelism with the beam-sharer. Once the relationship of the datum scale to the beam-sharer is achieved, it remains fixed throughout the alignment and assembly procedure (see Figures 6 and 7).

The beam-sharer design requires CCDs mounted in orthogonal planes. Because of this, duplicate fine motion mechanisms were provided. The mechanism that mounts the "transmission" CCD allows fine motion in the X, Y and θ coordinates as defined in Figure 6. In addition a two-step plunge motion is provided along the vertical (Z) axis. This permits loading the CCD underneath the indexing plate and then plunging the CCD upwards to within a few thousandths of an inch of the beam-sharer. After preliminary alignment, the CCD is carefully moved into spring-loaded contact with the beam-sharer face and final alignment is made. The mechanism that mounts the "reflection" CCD provides fine motion in X, Z and θ coordinates with a similar plunge action in the Y axis.

The fine motion in the X, Y and Z axes is controlled by a differential screw for each axis. Fine angular motion in the θ and θ axes is provided by tangent screws operating about the Z and Y axes respectively. The vertical (Z) axis is normal to the transmission output face of the beam-sharer while the Y axis is normal to the reflection output face. Motion of the respective CCDs in the Z or Y directions (the plunge action referred to above) is performed by a retractable plunger, which provides spring loading to hold the CCD against the beam-sharer surface. The CCD, which is mounted in a dual in-line ceramic header is clamped to the end of the plunger shaft by means of a special metal plate with clamping notches. This plate is temporarily attached to the base of the header with EK910 and is removed after assembly is complete (see Figure 8).

Focal plane assembly

There are three alignment parameters of concern: the accuracy of [illegible] overlap CCD to CCD at the butt, [illegible] of the CCDs and the total error band and to[illegible] for the entire assembly.

The alignment machine is designed to permit fabrication of the focal plane assembly to the following minimum specifications:

1) 2 micrometers at overlap [illegible] pixel for the subject focal plane assembly).
2) ±12 micrometers coplanarity.
3) 3 micrometers total error band (deviation from a straight line through the center of the total array length).
4) Parallelism and location of the straight line to the edge of the beam-sharer to within 125 micrometers.

Overlap accuracy

[illegible] Figure 4 [illegible] marks were incorporated on the CCD at the first metalization step [illegible] the 1024 [illegible]. The fiducials of adjacent CCD devices on the beam-sharer can be seen simultaneously [illegible] achieved when the CCD is aligned to show a symmetrical pattern [illegible] Figure 3. The accuracy [illegible] CCD overlaps in focal plane assemblies fabricated with this alignment machine are within 2 micrometers.

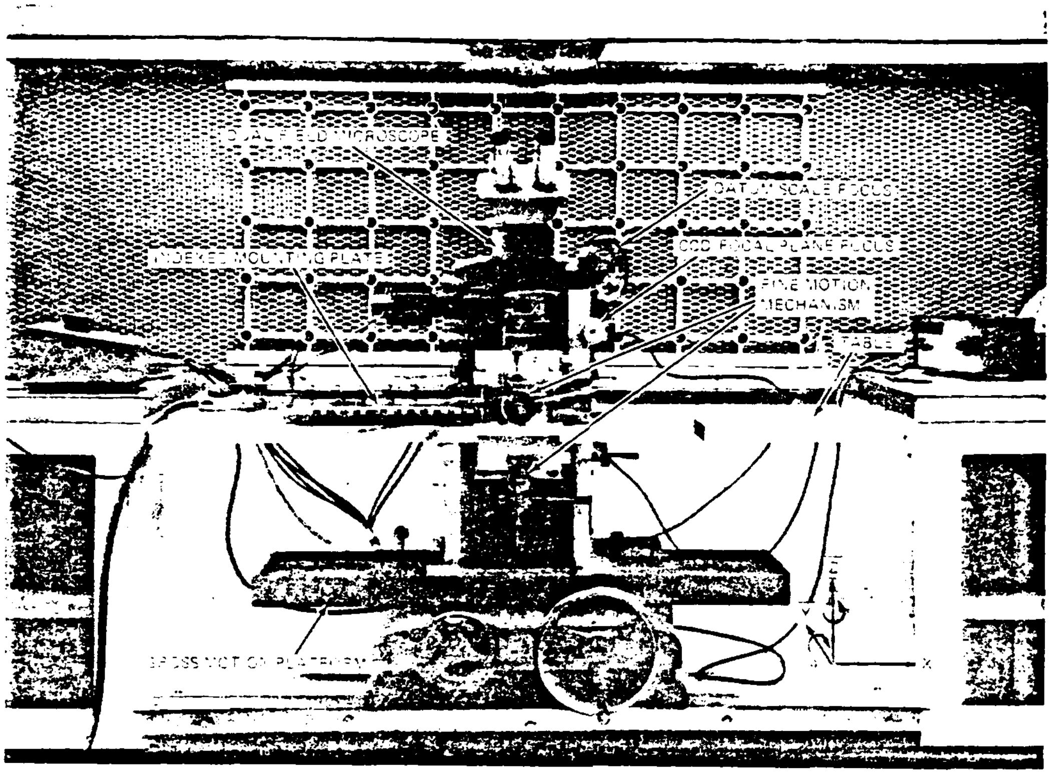
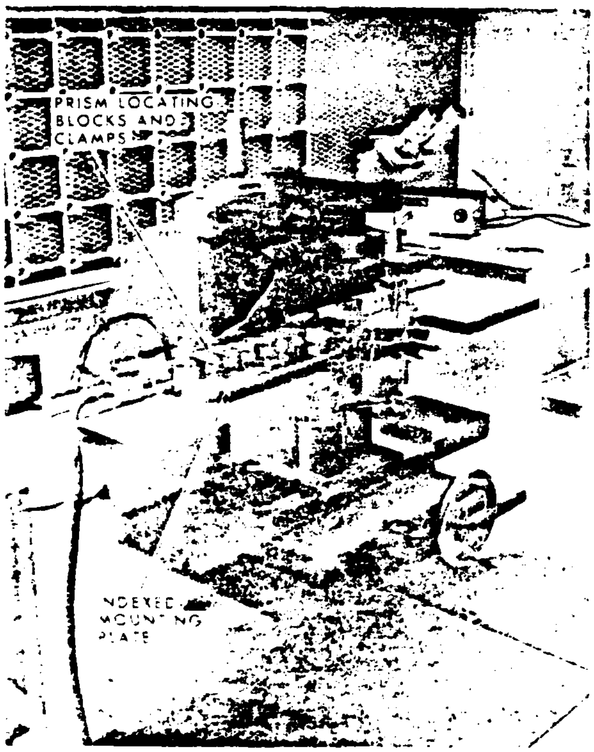


Figure 6. Front view of alignment machine.



[illegible] alignment machine

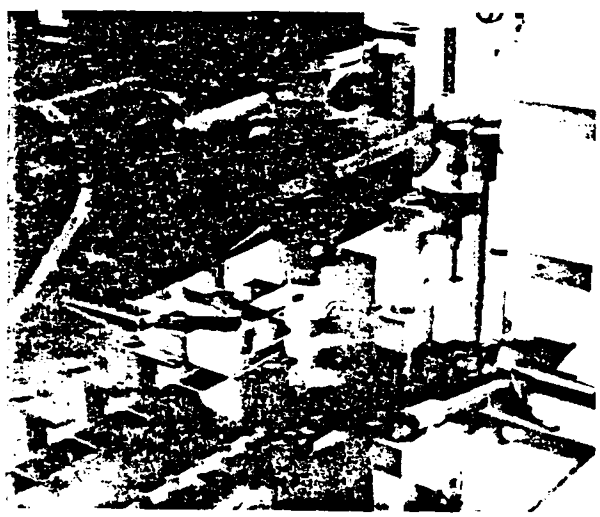


Figure 8. View showing beam-sharer and fine motion mechanism.

Coplanarity

The required coplanarity of the CCD is achieved by the use of a special ceramic header to which the CCD die is attached. Figure 10 shows a cross section of the package. During the fabrication process, the header is subjected to high temperatures, e.g., firing the ceramic layers and brazing of the pins and molybdenum base. Once these operations have been completed, the bottom surface of the molybdenum base is ground flat and parallel to the upper surface of the molybdenum base which is the die attach area. The top surface of the ceramic window frame is then ground flat and parallel to the bottom surface of the molybdenum base. It is this ceramic window frame surface that banks against the output face of the beam-sharer, thus, determining the CCD location relative to the beam-sharer's surface. The coplanarity achieved is ±12 micrometers.

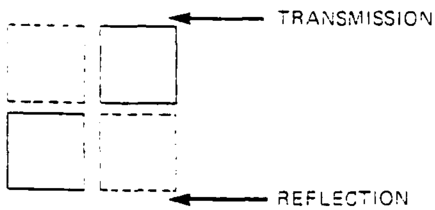


Figure 9. Overlap of fiducial marks from 2 CCDs.

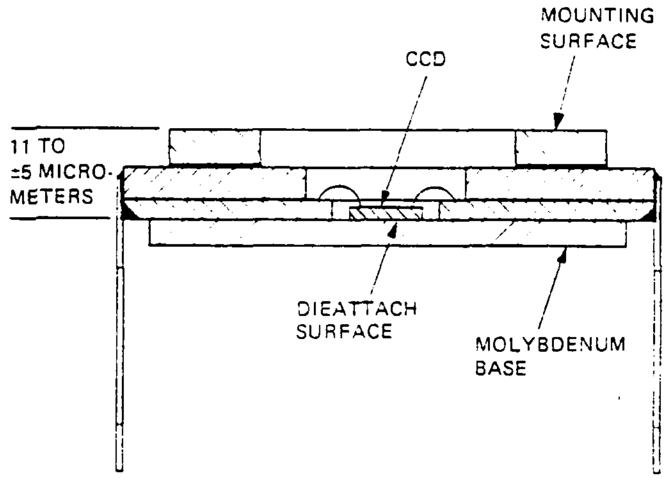


Figure 10. CCD header.

Total error band

A special datum scale was prepared, as shown in Figure 11, which serves as a master reference for the dual field microscope. The CCD fiducials are aligned to this master reference to keep the CCDs in a straight line. The total error band achieved for the 6,144 pixel long focal plane is ±3 micrometers.

Focal plane assembly procedure

The beam-sharer is banked against the locating blocks and clamped in place on the indexed mounting plate as shown in Figure 8. The transmissive surfaces are nominally centered over the access apertures in the indexed plate. This insures adequate range of the fine motion mechanisms about the nominal CCD position. The assembly procedure is outlined below.

Datum scale alignment

The dual field microscope is focused on the datum scale and the CCD channel is adjusted to focus on the edge of the beam-sharer [illegible]. While both fields are simultaneously observed, the eccentric cams are adjusted until the inner edge of the corresponding shaded [illegible] the datum scale (see Figure 11) is in coincidence with the beam-sharer edge. Parallelism is verified by scanning along the length of the beam-sharer using the cross motion platform. This procedure locates the center of the datum scale at the center of the beam-sharer.

The CCD channel of the microscope is then adjusted to focus on the centermost reflective/transmissive boundary at mid height in the beam-sharer. While being observed through the microscope, the datum scale is displaced laterally along the X axis until its [illegible] center line [illegible] lines up with the edge of the boundary. The datum scale is then clamped in place and parallelism is rechecked [illegible]. The [illegible] between the datum scale and the beam-sharer remains fixed until the focal plane assembly is complete.

[illegible] CCD

[illegible] CCD [illegible] the centermost [illegible] transmission or reflection [illegible] case the CCD [illegible] contact the beam-sharer and the CCD microscope is focused on the CCD fiducial nearest the datum scale crossed center [illegible] fiducials centered on these center lines. The cross motion platform [illegible] CCD fiducial is adjusted to [illegible] the center line of the datum scale. [illegible] must be applied to the CCD [illegible]

Cementing the CCDs to the beam-sharer

After initial coarse positioning of the first or any subsequent CCD, the indexed mounting plate with beam-sharer is moved out of the way. The CCD is removed from its clamping holder and an ultraviolet curing, polystyrene adhesive is applied to the ceramic window frame area. The CCD is replaced in the holder and the indexed plate is returned to its alignment position. The fine alignment of the CCD is then completed. Following this, the gross motion platform is used to move the entire assembly table out from under the microscope. Ultraviolet illumination is then applied in order to cure the adhesive.

Aligning the rest of the CCDs

Each subsequent CCD is then aligned to a previous CCD already cemented to the beam-sharer using the adjacent overlapped fiducial marks as shown in Figure 9. The fiducial at the other end of the CCD is then aligned to the datum scale reference lines to control parallelism.

The placement of the other CCDs proceeds outward in either direction from the center in order to split the total accumulated error over the entire array assembly.

Removal replacement of a CCD

In the event that it should be required, a removal technique has been developed which simply involves clamping a silicon rubber dam around the particular device and filling it with a solvent. This technique has been demonstrated for the prototype but has not yet been required in practice.

Conclusion

Figure 12 shows the first prototype beam-sharer focal plane assembly with six 1024 X 64 TDI CCDs. The effective focal plane is 6144 pixels long with 64 integrations. All of the design goals for alignment accuracy were met or exceeded in the prototype and subsequent assemblies. The actual system operation of the focal plane has been fully characterized.

Several advantages are realized with the beam-sharer focal plane assembly. They are:

1. High optical efficiency,
2. The CCDs are pre-packaged and can be fully characterized before application,
3. The focal plane assembly is repairable since any CCD can be removed and replaced,
4. Such a focal plane can be made to include a large number of CCDs.

The design of the alignment machine anticipated the need for longer focal planes in the future and the required capacity was built in. This unit has proven to be quite flexible. In recent months, it was used to assemble non-orthogonal, beam-splitter focal planes, several of which have now been completed with equivalent alignment accuracies.

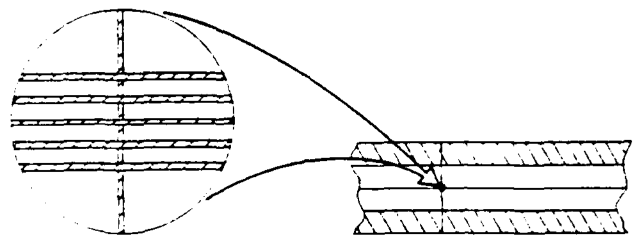


Figure 11. Datum scale.

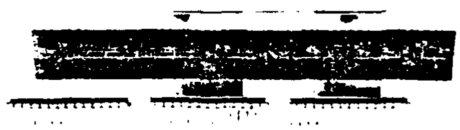


Figure 12. Focal plane assembly (photograph).

Acknowledgments

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LOW-CONTRAST IMAGING

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Paper presented at the SPIE/SPSE Technical Symposium
East, Reston, Va., 19 April 1977

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LOW-CONTRAST IMAGING

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Abstract

The evolution of electro-optical sensors has caused a quiet revolution in the imaging of low-contrast objects. In a practical sense, even the term "low-contrast" has required redefinition, since contrast ratios such as 1.6:1, which was the official "low-contrast" for photographic systems, no longer qualify as "low" for electro-optical systems which, by means of precise D.C. level background subtraction, can operate in the domain of contrast ratios around 1.01:1 and below. Since a contrast ratio such as 1.01:1 is below the contrast resolution threshold of the eye, the invisible can literally be made visible. This paper reports upon some of the fundamental constraints placed by nature on the development of such low-contrast imaging systems. It further describes the evolution of the specifications for an advanced technology Time Delay and Integration (TDI) type of area imagery Charge Coupled Device (CCD) which is being developed to meet present and future needs for this type of electro-optical sensor system.

Introduction

The goal of being able to thwart the natural conditions which limit the usefulness of both vision and photography in extracting information from scenes of vanishingly low apparent object contrast has been pursued with only limited success for many years. The use of short wavelength cut-off filters, for example, combined with the long wavelength end extension of photographic film sensitivity has helped to penetrate the veil in cases where contrast has been reduced by wavelength dependent (Rayleigh and Mie) scattering. The introduction of infrared sensitive emulsions carried this photographic approach about as far as it could go.

Other types of imaging systems operating both in the visible and near-infrared portions of the spectrum (classified as electro-optical imaging systems in this paper) and relatively long wavelength infrared (FLIR) sensor systems have been developed which can detect, quantify and display significantly lower "contrasts" than those possible with conventional "photography." The common properties of these systems which allow them to perform at low contrast include wide dynamic range and a high level of linearity. These properties in turn allow for subtraction of an absolute D.C. background level; effectively A.C. coupling carried to an ultimate extent.

It is not our intention to discuss FLIR systems at any length here. It is interesting to note in passing, however, that a hypothetical infrared system that can "resolve" (at or near its geometrical limit of detector resolution) a rather modest "least resolvable temperature difference" of 0.2°C against a background of 300°K, for example, is in a very general way essentially resolving an image with a "contrast ratio" of "$\frac{300.2}{300}$" or 1.003:1 – a rather respectable goal for a visible spectrum electro-optical imager. Extrapolation from this example may be used in part to forecast the future of visible spectrum low-contrast imaging.

As will be developed subsequently, another key to successful low contrast imaging involves the required collection of sufficient quanta so that the statistical "noise-in-signal" can be overcome.

If one considers a linear multi-element photosensor used to scan a scene in such examples as panoramic or strip mode cameras operating from an airborne platform, it can be shown that the exposure times needed to produce the number of signal electrons required for a useful signal to noise quickly places limits on focal length, aperture, field of view, and ground resolution. The problem is similar to the one posed in the case of a photographic camera forced to operate with an extremely narrow exposure slit. Perhaps not too surprisingly, the answer lies in the same direction which would be indicated for the film camera. Namely, "open up the slit width." In order to accomplish this electronically, a new type of sensor chip is desired – one in which image motion and the signal electron generation process can be essentially spatially synchronized, just as image and film motions are synchronized in a film camera. Such sensor chips have been produced already, and are undergoing continuing development for low contrast imaging applications. The rudimentary principles of their operation, and the development of specification goals for a sensor of this type are presented subsequently.

Long Range Sensing

One of the most probable applications for low contrast imaging systems is in airborne reconnaissance where the problem is one of obtaining useful information over long slant ranges when atmospheric degradation has reduced the apparent object contrast available at the entrance pupil of the system to a very low value. It is the object of the electro-optical low contrast imaging system to render such scenes visible.

Such electro-optical high resolution image sensing at long slant ranges through the atmosphere is encumbered by all of the classic problems of photographic aerial reconnaissance such as the vehicle stability, the necessity of thermal environmental control, vibration isolation, image motion compensation, etc. Some electro-optic sensors (among them being charge coupled devices or CCD's) are also possessed of the ability to subtract a background level from a combination of background plus signal, which permits them to extract intelligence from scenes in which the contrast level falls much below the limit of detectability for conventional photographic systems. While results from utilizing such subtraction techniques appear spectacular, there is no magic. Functioning systems must obey fundamental physical principles. Since resolution, contrast rendition, coverage, and bandwidth considerations (if the system is to record or transmit the acquired data) all, in a sense, "compete" for system's attention, the long range image sensing problem is seen to be one of obtaining the most efficacious compromise among these several factors.

Fundamental Performance Limitations

All other things being equal, the spatial resolution, measured most conveniently in micro-radians per line pair, available from an electro-optical system will be determined fundamentally by the diffraction aperture of the optical system employed. Also, the amount of light which may be collected in a given exposure time from an object of specified angular subtense will be determined solely by the diameter of the receiving aperture. Thus, while focal length may be scaled to accommodate a variety of sensors or detector element sizes, it remains the aperture diameter alone which controls both the potential response as a function of spatial frequency in the object space (micro-radians/line pair) and the amount of energy collectable from an object of prescribed angular dimensions in that object space. It is easy for confusion to arise about this point, and most important that it be dispelled early-on in any system parametric design. Consider a given circular diffraction aperture A. For incoherent radiation of a fixed spectral bandwidth the response of the aperture as a function of "resolution" (spatial frequency) in the object space (conveniently measured in micro-radians per line pair) is constant regardless of the focal length and resulting F-Number. As a further example, let us examine two optical systems both of aperture A, the first operating at F/2 with a sensor composed of 2 μm square detector elements and the second working at F/40 with 40 μm square detector elements. For a given uniform object apparent brightness level, the image illumination levels will vary by a factor of 400:1. However, since the larger detector elements have 400 times the area of their smaller counterparts, all things being equal, an equal number of photo-electrons will be generated per detector cell in either case. Also, in a strip or panoramic scan mode, the same angular image motion rate will result in the same image "dwell time" for either detector, again resulting in equal photo-electron generation. Both of these factors (diffraction limitation and light-collection ability) argue for use of the largest permissable collective aperture.

The level of resolution which can be achieved with a given overall system, in addition to depending upon the limits set by the optical aperture, is in part determined by the sensor characteristics, uncompensated image motions, and the level of correction of the optical system as well as by the degradation caused by vibration and the thermal environment. In addition, resolution is, of course, seen to be inextricably intertwined with scene contrast.

Charge coupled device based electro-optical cameras, in common with certain other types of electro-optical cameras, have an advantage over practical film based photographic systems in that, because of their large dynamic range and high linearity, it is possible to electronically subtract a uniform background level from the overall signal-plus-background, leaving the signal standing alone for subsequent amplification and display.

An inherent assumption in the establishment of feasibility of such a background subtraction scheme is that scattering media attenuate both high and low spatial frequencies in at least nearly the same way and to approximately the same degree. The idea here is that the effect of the scattering medium is to generally lower the response function curve all over rather than to lower it selectively at high frequencies. The first situation is represented by curves A, A^{I}, A^{II}, etc. in Figure 1, while the second is shown as curve B. The fact that the assumed condition is the more nearly true one has been demonstrated in many instances both for underwater experiments (Ref. 1) and in the atmosphere. The latter situation is probably best described by Middleton in his classic text Vision Through The Atmosphere (Ref. 2) from which the following brief quotation seems appropriate. "The 'ground glass effect' seems to be founded on popular belief. This was brought home to the author a few years ago when he saw a newspaper illustration showing a military exercise in the use of smoke concealment. Some men were shown at various distances in the smoke. Those nearby appeared in sharp outline, but fainter silhouettes of those a little further away seemed diffuse. The author was enough of a sceptic to call the office of the newspaper and ask to see the original print, which was duly removed from the file, and proved to have been retouched around the outlines of the more distant figures 'to make them look more natural.' Was ever a photographer more suspicious of the veracity of his camera? It goes without saying that existence of any phenomenon so generally accepted cannot be denied without a good deal of evidence."

A commonplace experience which also illustrates the fact that high frequencies are transmitted through scattering media is that of viewing the sun or moon through haze or fog. If the object is definable at all, its edges are usually sharp (containing high spatial frequencies) and not "softened" in outline by the intervening scattering atmosphere. While the scattering medium will transmit both high and low spatial frequencies, it will do so at sometimes drastically reduced contrast so that the eye, or conventional electro-optical systems would be unable to extract significant detail from the viewed scene. By utilizing the overall signal-plus-background, it is possible to subsequently amplify the signal so that the here-to-fore invisible scene is made visible.

However, just as the diffraction aperture places an impossible-to-exceed limit on the resolution capabilities of an electro-optical system, physical principles also prescribe the lower limit of contrast which can be perceived even with perfect subtraction. The ability to do such background subtraction depends, in a practical sense, upon the element to element uniformity of the sensors coupled with the ability to individually characterize and calibrate them. It also depends on the uniformity of the background itself on a picture-element to picture-element basis. Techniques for making charged coupled device sensor elements uniform, and for calibrating them, have been developed, and are in "inventory." But first, let us look at the problems associated with the uniformity of the background, and how this sets the physical limit for contrast rendition.

When photons strike a photo detector and generate photo-electrons, this point in the imaging process usually constitutes the one at which the minimum number of events takes place. For practical purposes, the uncertainty associated with the arrival of photons and the generation of photo-electrons can be considered in terms of a Poisson distribution so that the uncertainty may be taken as the square root of the number of photo-electrons generated. This then constitutes the shot noise of the system. In order to quantify what level of shot noise is acceptable in the class of system under investigation, the work reported by Schade (Ref. 3) has been applied. Here it is shown that for a single pass (such as would be generated in a linear sensor array (strip or panoramic) camera) the signal-to-noise ratio for tri-bar targets necessary for those targets to be resolved 50 percent of the time, is 3.6:1 between a single bar and a single space. Throughout the remainder of this discussion we will describe such a single bar of a tri-bar target as a resolution element or "resel." This is distinguished from a picture element or "pixel" which represents a single photodetector site within the sensor array. The selection of the [illegible] [illegible] width and thereby the scale of the system will determine the number of "pixels" per "resel."

[illegible] resolution element (bar) and its adjacent space of the same area, we find that the number of electrons generated [illegible] the resolution element itself is equal to the number of electrons from the background plus the number of electrons from the [illegible] [illegible] electrons in the background alone constitutes the level of energy from the space [illegible] the number of

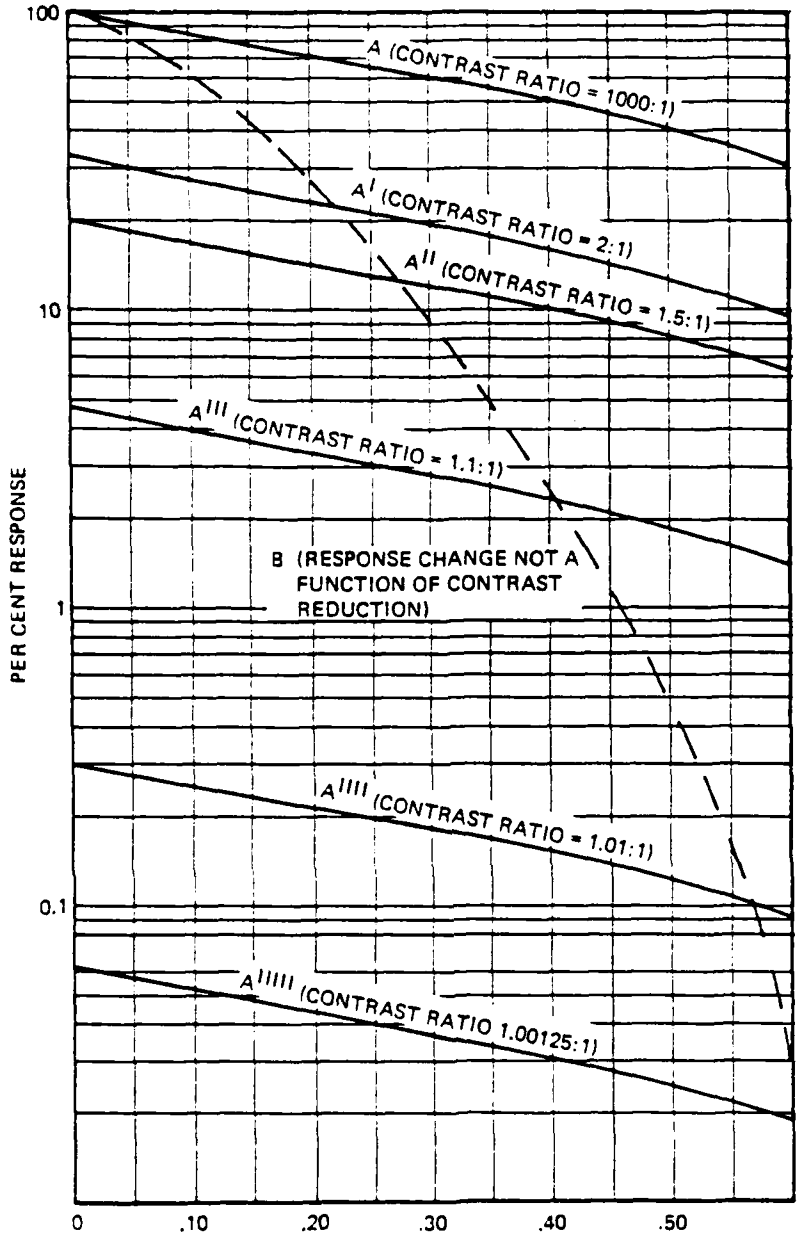

Figure 1. Relationship between contrast and frequency

electrons in the background and e_s the number of electrons from the signal, it is seen that for the shot noise limited case,

$$\frac{\bar{e}_b + \bar{e}_s - \bar{e}_b}{\sqrt{\bar{e}_b + \bar{e}_s + \bar{e}_b}} = S/N \qquad (1)$$

Using Schade's signal to noise requirement of 3.6 for a single bar, after mathematical manipulation, the expression reduces to

$$\sqrt{k} = 3.6\,\frac{\sqrt{\bar{R}_t / \bar{R}_b + 1}}{\bar{R}_t / \bar{R}_b - 1} \qquad (2)$$

Where k is the number of electrons required per resolution element in the image to yield a 3.6:1 shot noise signal-to-noise ratio and where R_t and R_b are the reflectivities of the target and background respectively. These relationships have been plotted in Figure 2.

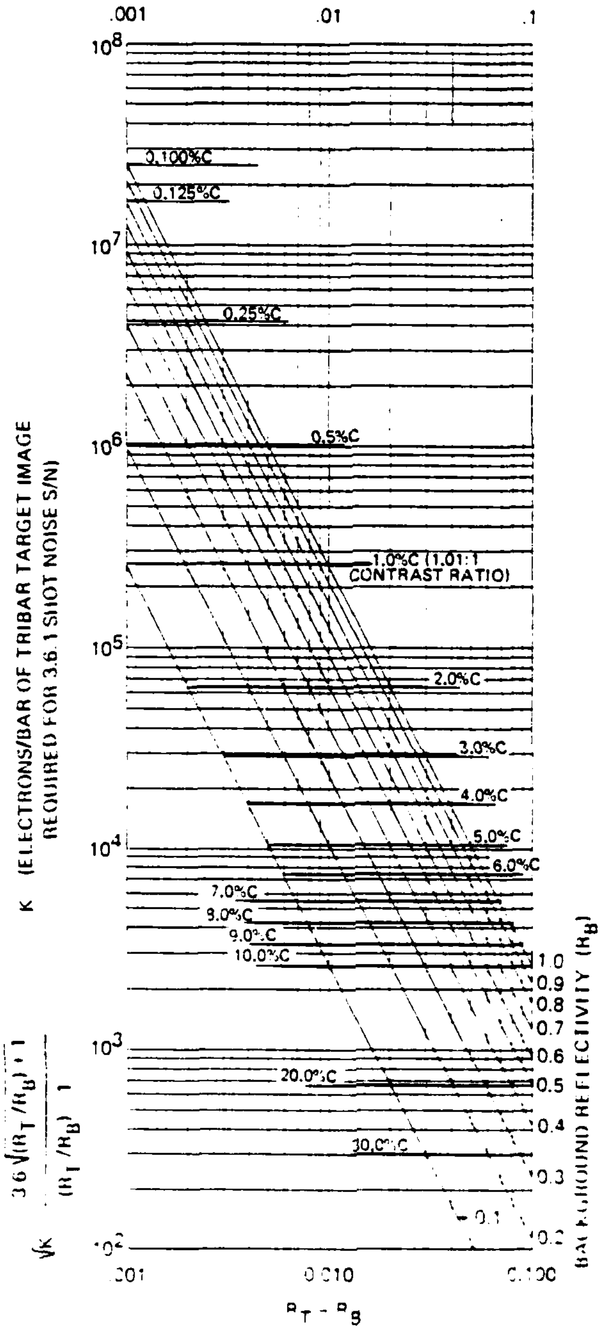

Figure 2. Relationship between background reflectance, target reflectance and contrast as these influence the number of photo electrons necessary to yield useful shot noise limited performance

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Getting Enough Electrons

The ability to collect sufficient electrons in small enough detector sites to provide optimum resolution lies at the heart of the overall resolution and contrast-rendition long range image sensing problem.

Unfortunately, under many of the real-world conditions addressed by the reconnaissance community, there simply doesn't begin to be enough light to fulfill the quanta requirements of eq. (2) for low contrast imaging, if one uses a linear imager (a line of photo detectors) and needs to provide a combination of useful field of view, resolution and electronic bandwidth. Solution to the system problem revolves simply around being able to obtain sufficient exposure at each photosite without unacceptable sacrifice of system operational parameters.

The T.D.I. Concept

To circumvent the exposure problems inherent in linear imaging sensors, the Time Delay and Integration (T.D.I.) mode of image sensor was conceived and developed. In a way, this type of sensor can be visualized as the electronic analogue of the exposure slit in a strip or panoramic mode of film camera. In the latter, an image moves accross the exposure slit. In strip cameras and some (moving film) panoramic cameras, the film is moved in synchronism with the image motion. Thus, the exposure slit can be as wide as the uncorrected motions of the vehicle and the degree of image and film motion synchronizer will permit. By this means high levels of exposure can be built up as needed.

For a description of our electronic analogue, reference is made to Figure 3. In this highly simplified diagram of a T.D.I. sensor chip, the architecture is composed of a series of columns (A, B, C etc) and rows (1, 2, 3 etc). Each row corresponds to a single photosensor in a linear imager. As the image crosses the sensor parallel to the rows, the photo-signal generated in each photosite is moved in synchronism with the image motion into the next photosite in the row where it is added to the charge generated there and subsequently moved on to the next photosite in the row, etc. until the summed signal is finally collected in a summation column which can in turn be read out as a shift register just as if it were a single linear sensor.

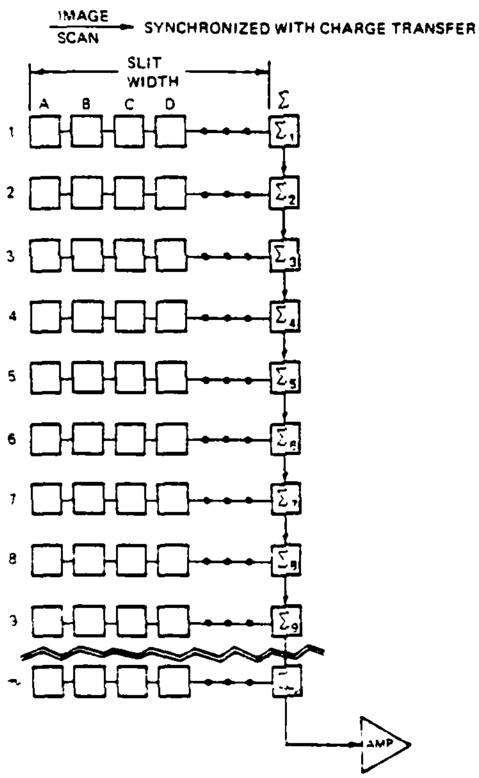

Figure 3. T.D.I. integrating linear array schematic

[illegible] sensor and a moving film type of panoramic camera is illustrated in Figure 4.

[illegible] T.D.I. sensor is not as uncomplicated as the above simplistic overview might imply. [illegible] each photosite can be considered as being divided into four [illegible] Transfer Function in the scan direction. While these complex[illegible] are [illegible] described more fully subsequently.

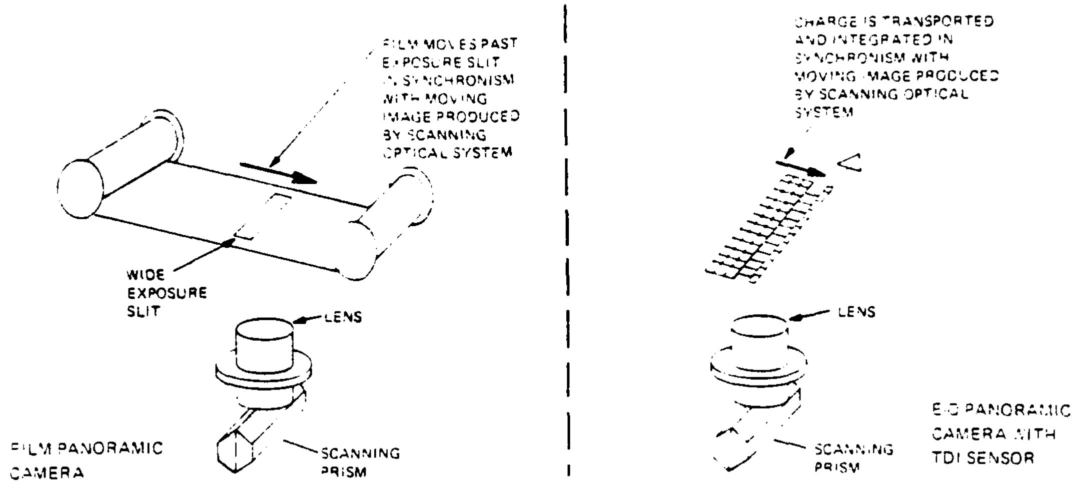

Figure 4. A comparison of two exposure integrating systems

System's Influence On Sensor Chip Design

The most formidable impact of low contrast imaging system requirements upon sensor design is, of course, the fact that exposures adequate for the development of the needed signal levels has necessitated the use of the TDI type of sensor. Beyond this however, considerable sensor chip design detail is dictated by general low-contrast imaging system performance requirements.

First, in order to operate in the scene brightness and contrast domain of interest, it is necessary that each photosite (pixel) be capable of developing a charge of about one million electrons. Since this value also forms a reasonable attainable saturation charge for a sensor chip, all would appear well insofar as operating with the number of integrations (columns in Figure 3) necessary to accumulate the desired charge. However, the perversity of nature presents us with not one, but a wide range of illumination levels. It is therefore evident that one of the first features that our low-contrast imaging sensor must have is a variable number of integrations so that scene highlights can be maintained at just below sensor saturation. This will give the largest signal (best S/N) possible consistent with scene brightness.

Since subtraction of background (D.C.) from signal-plus-background is an integral part of the low-contrast imaging process, accounting for any sensor signature must be made to a very high level of accuracy. This makes it desireable – in fact practically mandatory – that sensor signature due to variations in photosensor element area, responsivity, spectral response, and dark current be minimized beyond the "ordinary" variations in these variables.

Those types of requirements described above have led to the evolution of a Sensor Chip Characteristic Specification Goal for a T.D.I. type of sensor applicable to low-contrast imaging systems. A summary of those characteristics is presented in Figure 5.

1.	1024 X 64 element array with integration steps at 1, 4, 8, 16, 32 and 64 integrations.
2.	Q_{SAT} 10^6 electrons.
3.	Cell spacing 20 μM (20 μM x 20 μM pixel).
4.	Horizontal output rate 1.5 MHz, vertical rate 1.5 KHz.
5.	Dynamic Range: 3000 (0°C)
6.	Temporal noise: (0°C) dark [illegible] max
7.	Responsivity [illegible] Fairchild CCD 131
8.	V_{SAT} 1.2 V typical
9.	Photo Response Non-Uniformity (PRNU) [illegible] of sat. at 50% (0°C) 4 to 64 integrations less 5 spikes (objective).
10.	Avg. Dark Signal 0.25% of sat. (0°C)
11.	Dark Signal Non-Uniformity (DSNU) requested [illegible] of sat. – objective only.
12.	Bi-directional output register

Figure 5. Objective specifications for CCD TDI sensor chip

Summary

We have shown the physical basis which call for large numbers of electrons to be generated in order to make possible low-contrast electro-optical imaging. We have also described the principles of operation and the specified characteristics for a new type of sensor chip specifically intended for low-contrast imaging applications.

Much remains to be discussed with respect to the methodology of system development, including the "hows and whys" of such aspects of the systems problem as what portion of the "background" to remove, what background undulations should be subtracted, etc. It is hoped that these questions can be the subject of future communications.

It is safe to state, in any event, that the ongoing developments discussed here will further our ability to penetrate the invisibility curtain imposed by the nature of very low contrast scenes.

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The TDI Image Sensor For The LOREORS Camera

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Abstract

The design and operation of a 1024X64 element, time delay and integration (TDI) image sensor will be described. This image sensor array has been designed for minimum cell size consistant with a requirement for high signal-to-noise ratio, namely, a goal of 60dB near saturation. Since an inherent noise is the charge packet shot noise, the size of each charge packet near saturation must be at least 10^6 electrons. This has been realized using a 20X20um element, a four-phase CCD configuration in the parallel array registers, and buried channel CCD technology throughout the array. With four-phase buried channel CCD technology it was possible to achieve a charge handling density of close to $1X10^{12}$ electrons/cm^2 and also have the capability of handling very small levels of signal charge without need for a fat zero as would be necessary with a surface channel device. The active length of the array is 20.48mm (0.806"). Other features of the device are also described, including electronic exposure control. Full device performance has been achieved on initial sample parts; a cumulative charge transfer inefficiency in each direction of < 0.1 was achieved.

Introduction

The Long Range Electro-Optical Reconnaissance System (LOREORS) is an electronic camera system which incorporates an in-line array of line-scan CCD image sensors. Each of these image sensors is a monolithic integrated circuit (chip) with a resolution capability of 1024 elements. By making each of these elements a time-delay-and-integration (TDI) column with 64 stages of integration, each image sensor becomes a 1024X64 element array. The resulting sensitivity is 64 times that of a simple line-scan image sensor with square elements of equal size. This paper describes the design of the device and presents some early performance results.

Configuration of the Image Sensors in the Camera

In order to obtain a continuous line-scan image from a set of more than one image sensor chip, it is necessary to have some method of mechanically or optically butting the chips together. In the LOREORS camera a prism beam-sharer is used to form two image planes such that optically adjacent chips can be located in different image planes. This system produces no loss of imagery at the butts whatsoever. The configuration is shown schematically in Figure 1. As can be seen from this figure, the nature of the TDI sensor is such that if one desires to scan the output registers of the devices all in the same direction in the assembled system it is necessary to have both right-handed and left-handed devices since the basic TDI device does not have inversion symmetry. The device described here can be operated either as a right-handed or a left-handed device.

The TDI Concept and the Effect of Velocity Error

In order for a TDI column of sensor elements and delay elements to function to maximum advantage, the image velocity must be constant and equal to the shift velocity of the delaying structure. In practice this condition is never exactly met; there will always be small differences in speed and direction, as well as changes in these parameters. Figure 2 shows how MTF performance degrades as the difference in velocity increases. In this figure, f_N is the Nyquist spatial frequency, i.e., the highest resolvable frequency for the array, and N is the number of stages of integration. From this figure it can be seen for example, that if the velocities track to $\pm$ 1% and N = 50, the degradation is less than 13% over the full spatial frequency range. In this analysis the individual (square) element is assumed to have uniform response across its entire 20um length and to be moving continuously. In the LOREORS image sensor, the first condition is met but the second is not; the discontinuous nature of the motion is described next.

The motion of the Charge Collection Site

Each moving charge collection site within a CCD TDI column is defined at its front and back edges by the position of the crest of the potential barrier for electrons, since that is what dictates whether a particular photoelectron will drift to one potential well or to the adjacent one. The LOREORS image sensor employs a 4-phase TDI register. The 4-phase clocking can shift these potential barrier crests either 4 or 8 times per cycle, depending on the specific clock timing. Figure 3 shows the clocking method which produces 8 shifts per cycle; the clocking is defined in the figure by which phases are low at any time. The figure also shows the time-averaged response profile of the moving site. The loss of MTF at the Nyquist frequency for 4 moves per cycle is 2.6% relative to continuous motion (Ref. 1); for 8 moves per cycle the loss is 0.6%. Thus, the MTF curves in Figure 2 are accurate to 0.6% or better including the effect of TDI motion.

Description of the Image Sensor

A block diagram of the image sensor is shown in Figure 4. It shows the sensor array itself, the bi-directional output register and the two equivalent preamplifiers. The unit cell of the sensor array has a saturation charge level of slightly over 10^6 electrons. This provides a shot-noise-limited signal to noise ratio (SNR) of approximately 1000:1 near saturation. In an advanced system like LOREORS, where corrections can be made for array nonuniformities, this high-light SNR sets the limit to low-contrast image detectability. This saturation charge is achieved with a buried channel 4-phase CCD design provided the clock waveforms have at least two phases high at all times. The 20um element size is approximately minimum for a 10^6 electron capacity unless the basic CCD/MOS process is substantially modified or clock voltages swings in excess of approximately 10 volts are used. However, the latter is undesireable because of the increased dark current that results at defect sites.

Exposure control (EC) gates are located such that the number of TDI integrations can be adjusted from 64 to 32, 16, 8, 4 or 1. By appropriate use of these gates the saturation charge level can be kept near 10^6 electrons over a wide scene-to-scene dynamic range, thus providing a high SNR over this dynamic range. These gates operate by biasing any one of them to ground while all the other 4-phase gates and EC gates are operating together as one 4-phase system between two positive voltages, e.g., between 2 and 10 volts. Thus, in part of the array electrons are clocked forward and in the other part they diffuse backward in saturated, forward-clocking registers.

Another feature of this device is a special optical layer-thickness design which optimizes the broad-band response in the spectral range 500-900nm for the case of 5000°K blackbody illumination (Ref. 2). Spectra for the full optical design (with silicon nitride both above and below the polysilicon gates) and for a simplified version of it, taken on a developmental image sensor, are shown in Figure 5. These spectra correspond to broadband responsivities, for the above illumination conditions, of 135 and 105mA/W, respectively. These values represent improvements over a typical previous device of 20 and 50%, respectively.

The bi-directional output register has been designed so that only one transport clock is required. The circuit diagram in Figure 6 shows the four required drive terminals for this register. The terminal codes indicate how these are interconnected to operate the device in one direction or the other; for example, terminal "$Ø_{HR}/V_{HL}$" is to be tied to $Ø_H$ for right-hand operation and to V_H for left. ($Ø_H$ denotes the transport clock.)

The preamplifiers may be described as resettable floating gate amplifiers; they are shown in Figure 6. This very simple amplifier circuit was chosen in order to obtain a high degree of stability and linearity as well as low noise. When the floating gate potential is reset once each line period, the only high-frequency clock coupling is due to the transport clock. By optimizing the value of the load resistor for the particular operating frequency and the particular following stage characteristics it is anticipated to achieve a minimum noise equivalent input signal (NES) for a variety of operating conditions. The NES at 1 Msps is less than 200 electrons/pixel on first sample devices but how much less has yet to be determined. At a signal level of $5X10^5$ electrons/pixel this preamp noise decreases the device SNR by less than 4%.

MTF as a function of wavelength at the Nyquist frequency has been estimated by measurement and is typically > 60% for wavelengths less than 700nm, 45% at 800nm and 30% at 900nm. For the case of unfiltered 5000°K illumination the MTF is typically 50%.

An Imaging Test That Does Not Require Precision Image Motion

This image sensor has been evaluated with the use of a flash illuminator. In this test the (TDI) 4-phase clocks are operated continuously just as they would be in a TDI camera, and the illuminator is flashed once every 64 or more line-scan periods. The device is illuminated directly (without any optics), producing an image of the nonuniformity pattern of the array in two dimensions. Such an image is shown in Figure 7. The 16:1 aspect ratio of the image sensor has been altered slightly at the display to better show the details. This picture was taken at close to 10^6 electrons/pixel; the total gray scale of the picture covers a contrast range of approximately 5%. Thus, there are features visible here that are of the order of 1% in contrast; consistant with design calculations, high frequency temperal noise does not appear in the contrast range. (Line-to-line temperal noise seen in this picture is kTC noise which may be avoided by line-clamping.) The only clearly discernable dark signal features are two vertical white lines on the right; these are 2% contrast features.

TDI-Mode Response Uniformity and Dark Signal Uniformity

Since the TDI-mode uses each sensor column as a single element, spatially-small nonuniformities in both the response and the dark current are averaged over each column. Thus, the major nonuniformities in a TDI-mode image are typically due to long-range shading effects and to very large dark current "spikes". Figure 8 shows a photoresponse scan which is seen to be uniform to approximately ± 3% over the length of the device, with local uniformity being much better.

The two dark current "spikes" causing the 2% contrast lines in Figure 7 are actually caused by square elements with dark currents of over 20 times the background. In the TDI-mode the dark signal output for these TDI-columns was less than twice that of the background.

Conclusion

A 1024X64 element TDI image sensor with several special features has been described, and low contrast non-TDI-mode imaging has been reported.

Acknowledgments

The development of this image sensor was funded by the Fairchild Imaging Systems Division as an IR&D item. The sensors are being used on the Air Force LOREORS program, Contract #F33615-76-C-1282.

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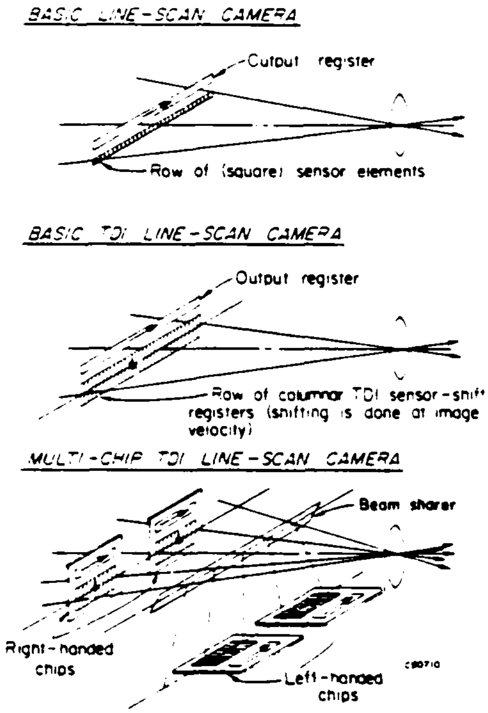


FIG. 1 EVOLUTION OF THE MULTI-CHIP TDI LINE-SCAN CAMERA

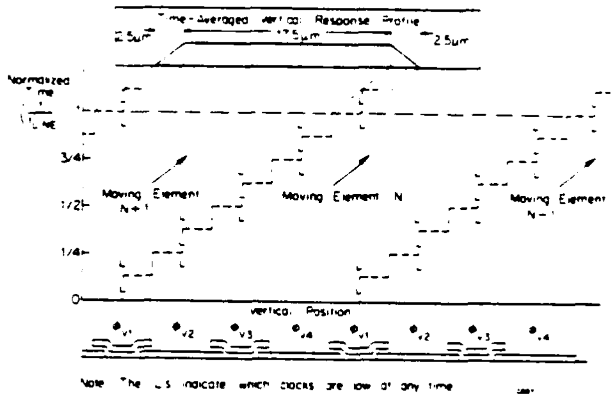


FIG. 3 TDI ELEMENT MOTION IN THE 4-PHASE REGISTERS

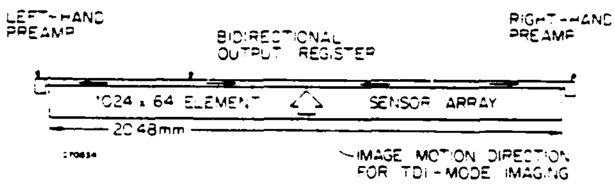
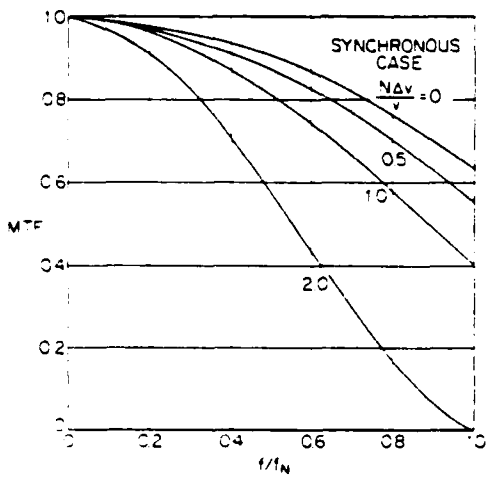


FIG. 4 BLOCK DIAGRAM OF THE IMAGE SENSOR CHIP



$$MTF = \frac{\sin\frac{\pi}{2}\left(\frac{f}{f_N}\right)}{\left(\frac{f}{f_N}\right)} \cdot \frac{\sin\frac{\pi}{2}\left(\frac{f}{f_N}\right)\left(\frac{N\Delta v}{v}\right)}{\left(\frac{f}{f_N}\right)\left(\frac{N\Delta v}{v}\right)}$$

FIG. 2 EFFECT OF VELOCITY ERROR ON MTF

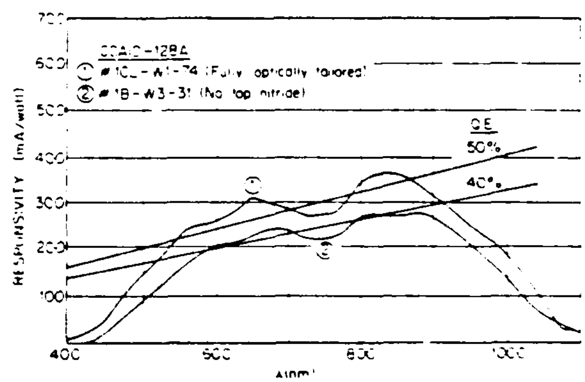


FIG. 5 ABSOLUTE SPECTRAL RESPONSE OF A PHOTOTYPE IMAGE SENSOR OF SAME CONSTRUCTION AS THE 1024X64-ELEMENT DEVICE

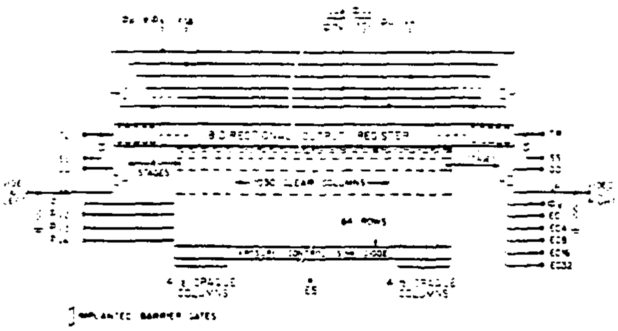


FIG. 6 CIRCUIT DIAGRAM OF THE 1024X64-ELEMENT IMAGE SENSOR

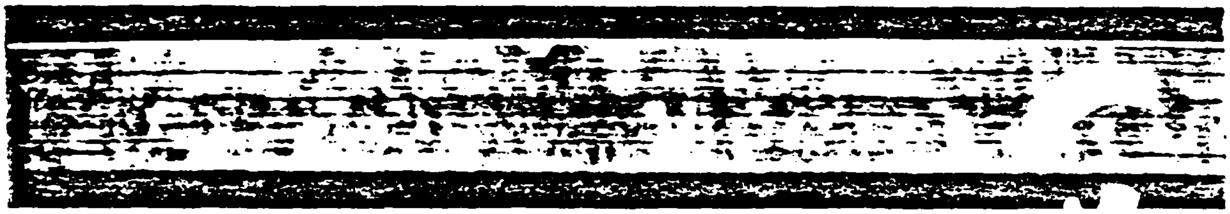


FIG. 7 SELF-IMAGE OF THE 1024X64-ELEMENT IMAGE SENSOR TAKEN AT HIGH GAIN (SEE TEXT)

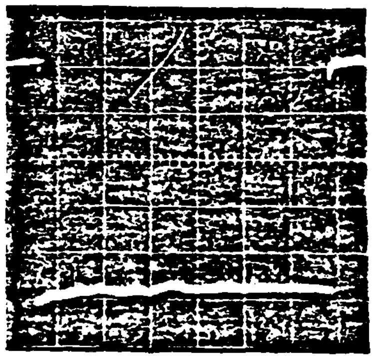


FIG. 8 TDI-MODE PHOTORESPONSE UNIFORMITY FOR THE SAME DEVICE AND CONDITIONS OF FIG. 7

All of Appendix B is unclassified

APPENDIX B

AIRCRAFT WINDOW THERMAL SHOCK

An analysis of aircraft window thermal effects was undertaken to determine whether rapid vehicle descent would cause excessive destructive forces with rapid temperature and pressure changes. Various methods for the maintenance of uniform temperature gradients, across the internal window surface, were also investigated. It was anticipated that an operational restriction might be required to limit the maximum allowable aircraft descent rate below altitudes of 10,000 feet to protect the window.

Inquiries were made of various aerodynamicists and thermal experts to ascertain whether the thermal shock problem had been previously analyzed. It was found that these experts used contradictory assumptions and generally disagreed on the solution to this problem. Therefore, the task of physically developing a realistic model and selecting an appropriate mathematical technique were addressed. A practical method for calculating the window thermal stress was evolved. As a result of the initial calculations the following results wer obtained:

Descent Time (From -45°F to +85°F Air)	Maximum Tensile Stress	Inner Surface Condition
0 Minutes	2200 PSI	Free
10 Minutes	1300 PSI	Convection
20 Minutes	1600 PSI	85°F Air

The maximum allowable tensile stress for the interior of the glass window is about 3000 PSI. However, the safe allowable stress should be less; about 1000 PSI for either interior or exterior surfaces. Exterior surfaces are prone to damage and erosion which tend to induce stress points, thus the lower figure should be used for

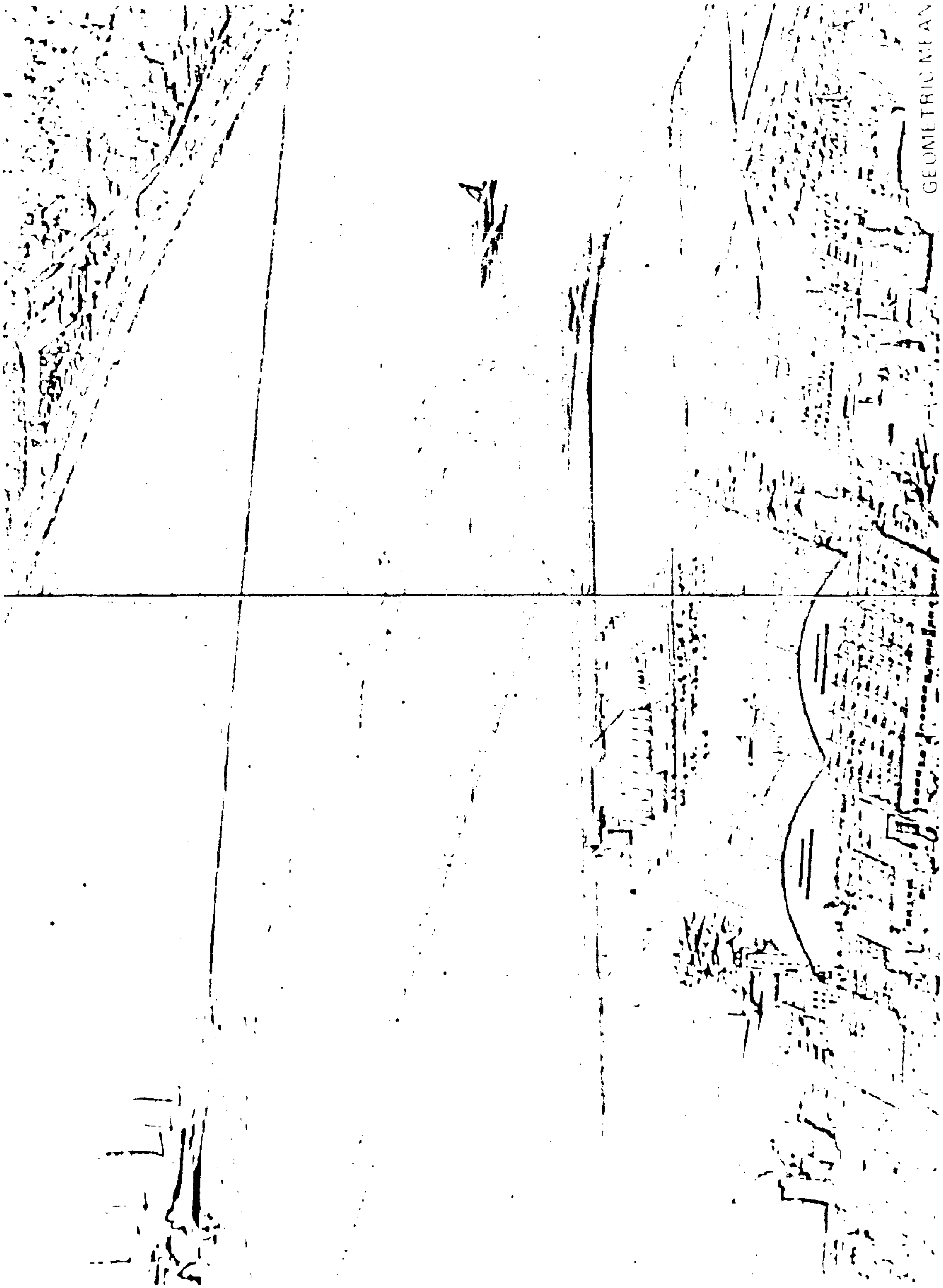


PHOTO PRINT C8

C3. LOREORS Flight Imagery from Flight 11

(C) Imagery obtained from the eleventh flight, flown on May 15, 1980 are shown in prints C8 through C11. These prints are small sections of the original scans enlarged four times. The scale in these prints, taken at slant ranges varying from 11 to 30 nautical miles, yields excellent detail enhancing image interpretation. While there still appears to be a minor stabilization problem as evidenced by the the slight waver in scan direction edges, the accurate reproduction of minute detail, such as the lines in the parking lot, is impressive. Compression of the contrast range by attenuation of the low frequency background signal greatly increases the information content in these prints.

(C) Print C8 slant range is 28.7 NM, print C9 slant range is 30.5 NM, print C10 slant range is 11.4 NM, and Print C11 slant range is 28.8 NM.

PHOTO PRINT C7

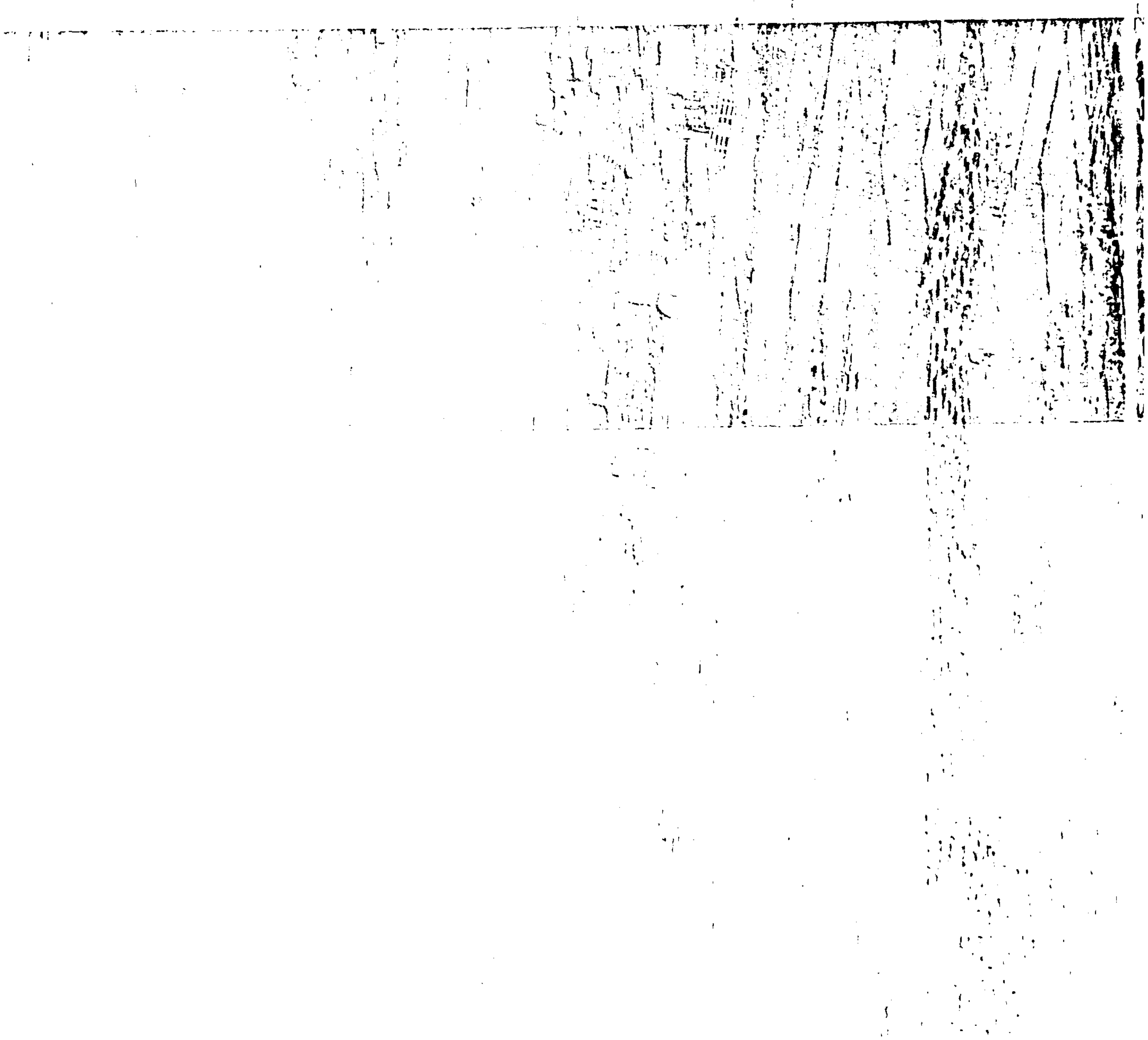


PHOTO PRINT C6

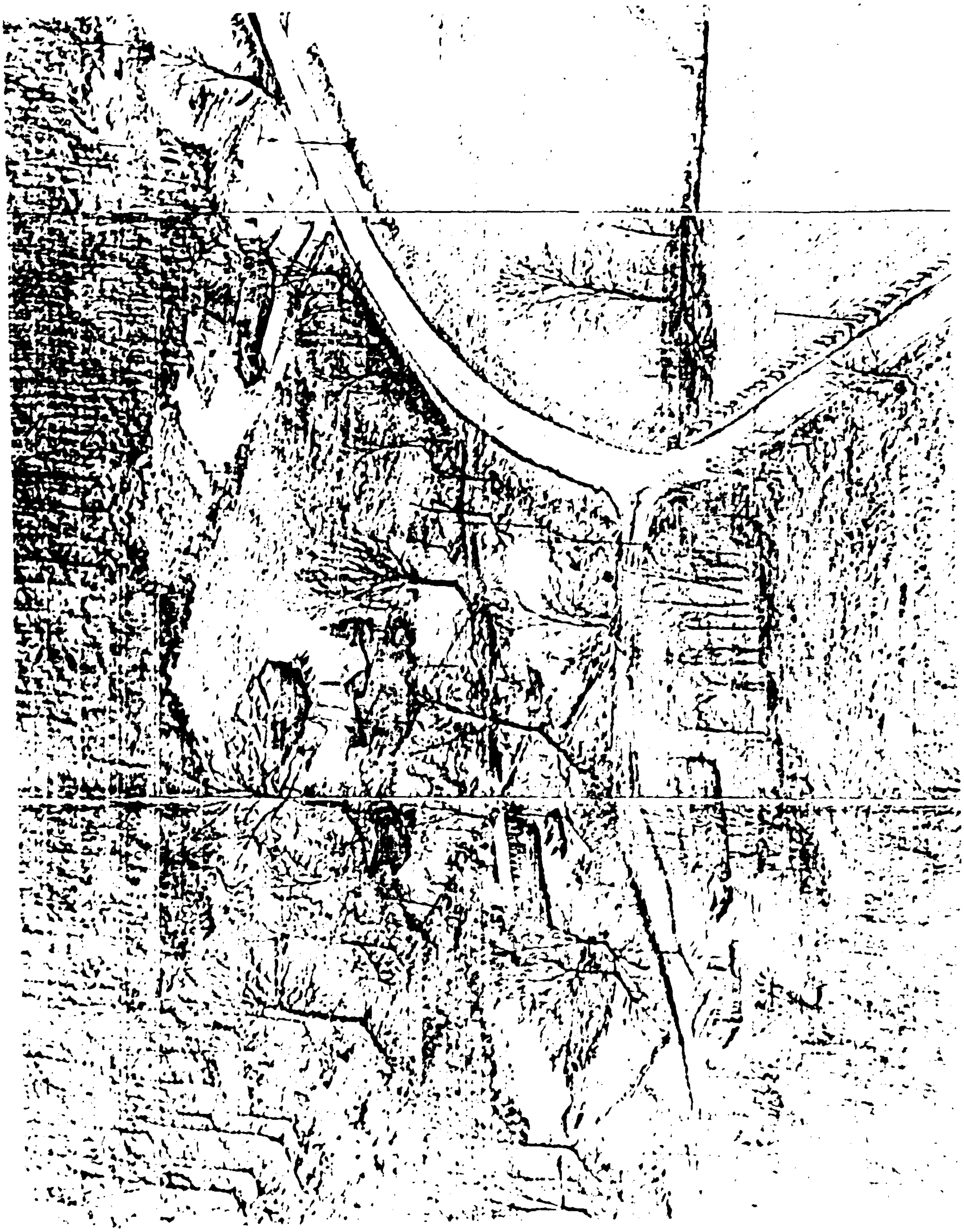


PHOTO PRINT C5

C2. LCREORS FLIGHT IMAGERY FROM FLIGHT 3

(C) Imagery samples from the third flight flow on April 5, 1980 are included as photos C5 thru C7. C5 imagery was taken of scenes around Wright Patterson at altitudes of 10,000 and C6 & C7 were taken around WPAFB at 29,000 feet. The higher altitude scenes were taken at a mid frame range of 45 nautical miles. It was estimated that the scene contrast at which these photos were taken was down around 1.000:1.

(U) The FMC problem has been cleared up and the skewed scan has been eliminated, but it is apparent from the "Atlantis" effect (the buildings appear to be sinking) we still had stabilization problems.

(C) At the lower altitude, at a range of 10 nautical miles, enlargements of the imagery appear steadier.

PHOTO PRINT C4

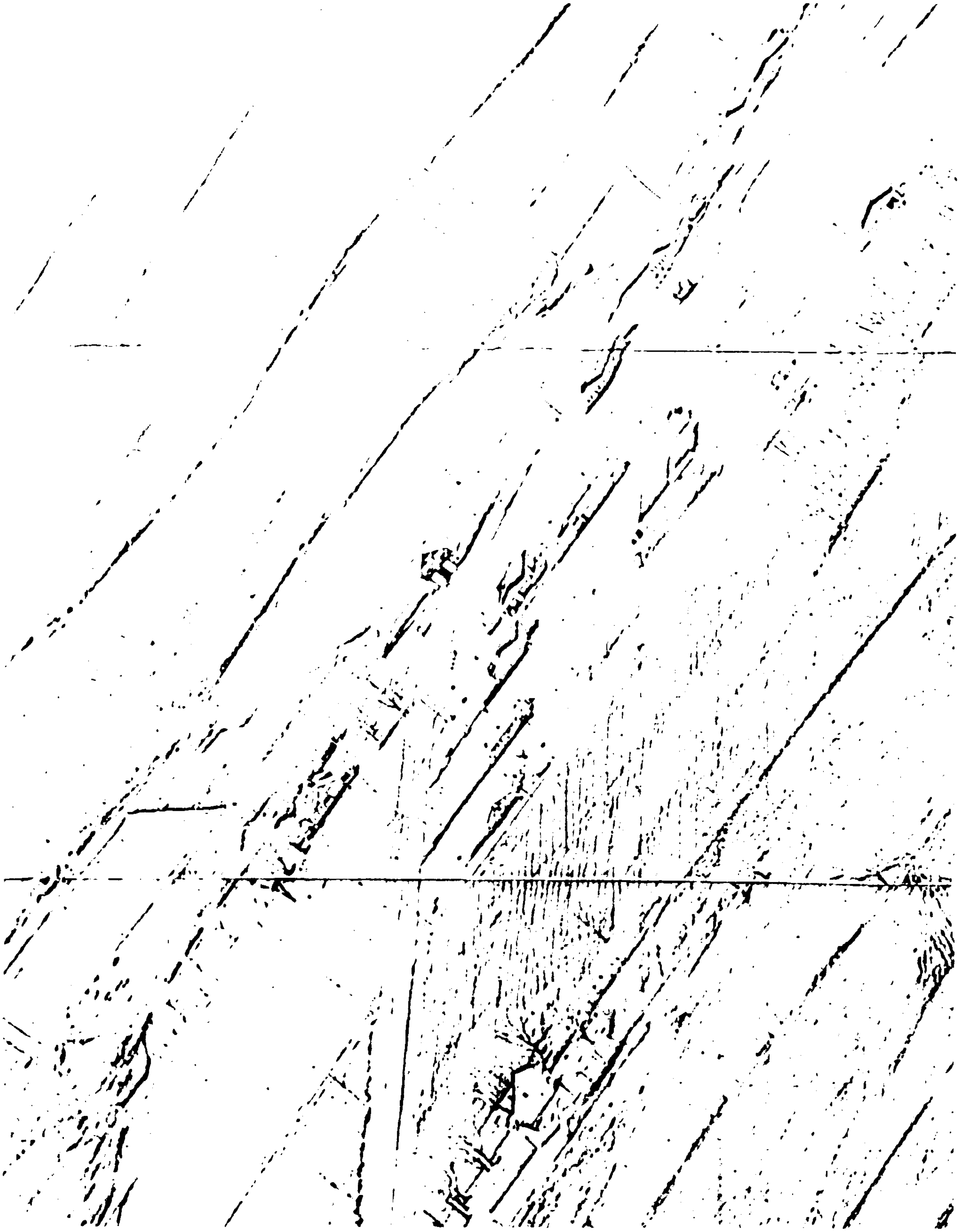


PHOTO PRINT C3

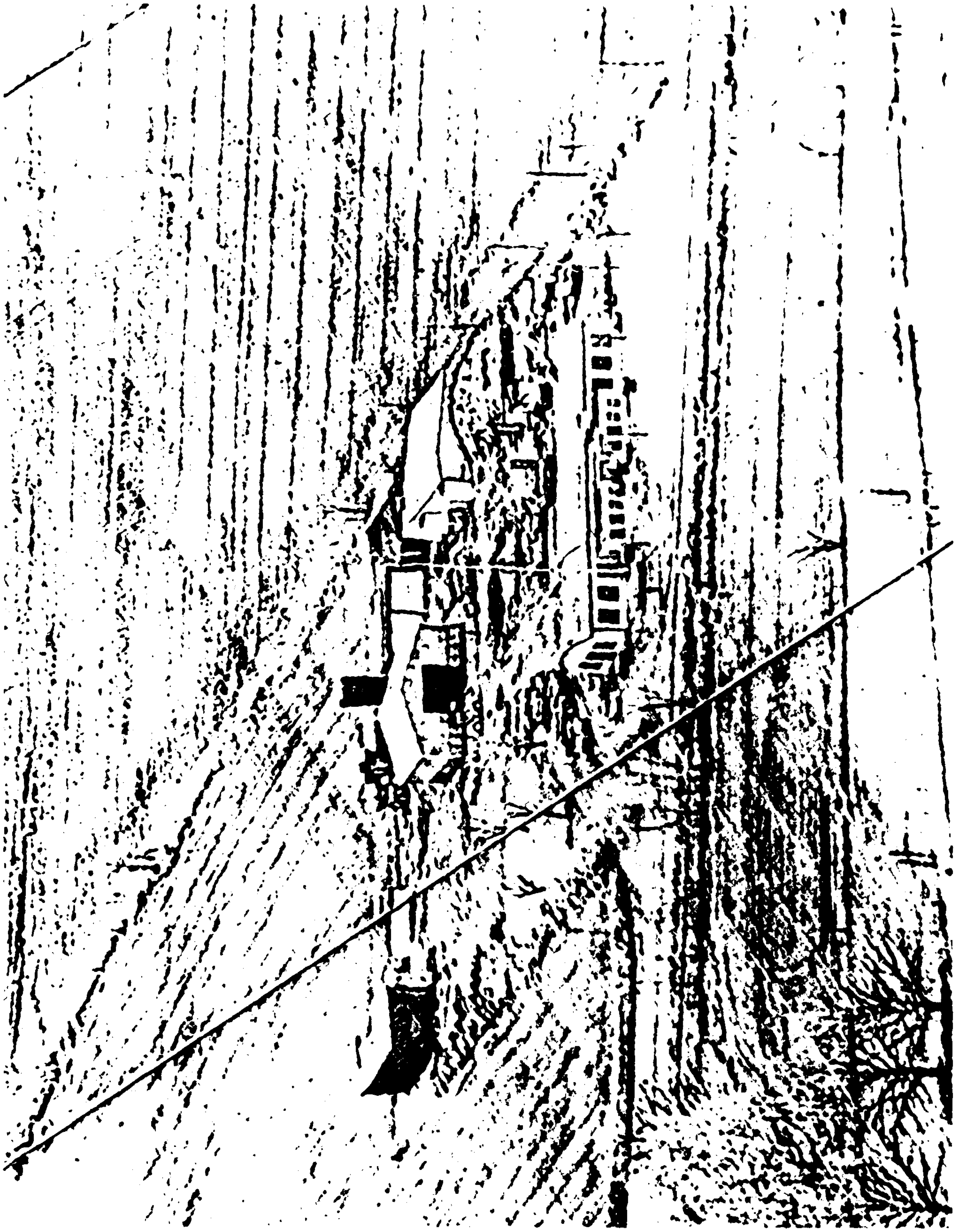


PHOTO PRINT C2

PHOTO PRINT C1

APPENDIX C

C1. FLIGHT TEST IMAGERY

(U) Representative examples of the imagery resulting from the flight tests are presented in this section. As the hard copy images are scanned, from the flight test which started in March 1980 and continued through June, the progressive improvement in the image display is evident. Seventy-three hours of flight time was logged during these tests and useable results were returned almost all missions.

(U) Examples of thie initial flight test imaging are shown in the prints labeled C1 through C4. The first mission was flown on March 6, 1980 at an altitude of 10,000 feet with image scanning ranging from 7.5 to 13 nautical miles. Although the visibility was not measured there was some cloud cover present. On this first flight the sensor scanned the scene, however the FMC malfunctioned and the rear bearing was not operating properly. These problems are evidenced in the prints as skewed scan.

(U) The photographic quality in these first returns were not up to par, but these prints did contain an impressive amount of detail. Telephone poles and fence stakes could be ascertained. Buildings, mostly single family homes and some barns show up with door and window details. From these typical details the resolution in these photo were estimated to be in the range of three feet per pel.

(U) Photo print C2 is an enlargement of an area of photo print C1 and photo print C4 is an enlargement of photo print C3.

This design approach was implemented as follows: Strip heaters were oriented in 4 bands around the sensor window frame. Each band is separately controlled. In addition, provision is made to mount low thermal inertia heaters in the 1-1/2" gap between the windows, should heat in this area prove beneficial. The gap is vented to the aricraft ambient air through a dessicant canister. To help raise the temperature of the inside sensor window surface, the cooling air flow in the scan head is reapportioned to include a larger flow rate in the window area.

Fittings are also to be installed, together with adjustable air jets to allow the introduction of compressed air from the air bearing compressor into the 1-1/2" space between the windows for the purpose of momentarily mixing the air in the gap to break up convection air currents immediately prior to scanning. Final optimization of the heat balance of the sensor window and timing of air mixing was determined during flight test.

The external window frame was fabricated from reinforced fiberglass material for thermal insulation purposes. A preliminary design using glass cloth per MIL-C-9084 class 2, Type VIII and an epoxy resin per MIL-R-9300, type 1, class 1 was approved. Fiber glass was an acceptable material for the proposed design.

pressure between the two windows. This was found to be unacceptable in the design configuration because a large pressure differential would exist across the thin window nearest the camera.

The pressure differential problem could be overcome with a design which placed a one inch window on the outside and a 3 1/2 inch window facing the camera. A separation of 0.225 inch would be maintained between the windows and this volume kept in pressure equilibrium by the pressure outside the aircraft. This configuration was analyzed with an additional degree of freedom, namely, the nature of the gas occupying the space between the windows. With dry air filling this space at a pressure equivalent of 40,000 feet (3psi) the thermal conductivity would be only 75% of that for air at 10,000 feet (11psi). The advantages of other gasses are seen by examining the thermal conductivities tabulated below:

THERMAL CONDUCTIVITY K FOR GASES AT STP

GAS	MOL WT/AT WT	K $\frac{\text{BTU-FT}}{\text{FT}^2\text{-HR-°F}}$
AIR	-	0.015
NITROGEN (N_2)	28.0	0.015
ARGON (A)	38.9	0.01
FREON - 12	121.0	0.0056
KRYPTON (Kr)	83.8	0.005
XENON (Xe)	131.0	0.003

Further analysis of the thermal characteristics of the aircraft sensor window design were made. The model analyzed was as follows:

- ° 1" thick outside window
- ° 1/1/2" air gap at 40,000 ft. pressure
- ° 3" thick inside window, and
- ° heated mounting frame at 55°F, 70°F and 85°F.

This combination produced the best overall temperature profile for the windows.

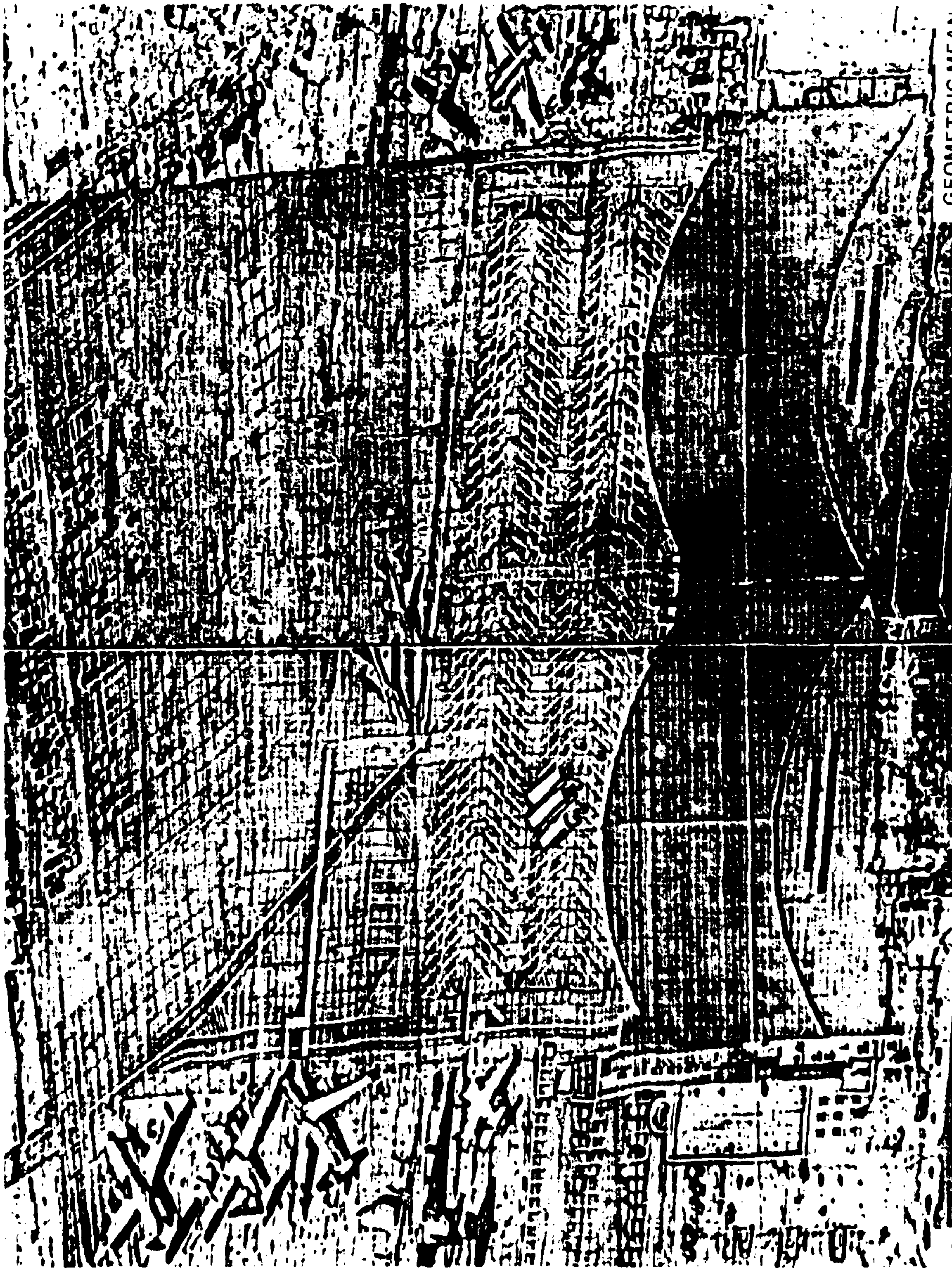
exterior surfaces under all conditions. For the case at hand, the maximum glass stress developed, after a time, near the middle of the window. An initial prediction based on the results above indicated that the safe descent time should be approximately one hour.

These analyses of the thermal gradients across the surface of the aircraft and sensor windows found the temperature changes to be within acceptable limits with the use of the environmental control system initially planned for sensor design. However, the temperature difference between the inner surface of the aircraft window and the outer surface of the camera window was large and could approach a marginal conditions. Additional investigations of the proposed design were performed in an effort to reduce the temperature difference. It was felt that increasing the air flow on the inner surfaces would alleviate this situation.

Analyzing the thermal characteristics of the thick Aircraft and thin sensor windows verified the existence of a large temperature difference between the inner surface of the outer window and the outer surface of the inner window. This temperature difference coupled with the relatively large separation of the surfaces (2 inches) would cause convection currents that could optically degrade sensor performance. These convection currents could be eliminated by reducing the space between the two windows to less than 1/4 inch. This required mounting both windows in a single frame in the aircraft and providing a flexible boot to the camera.

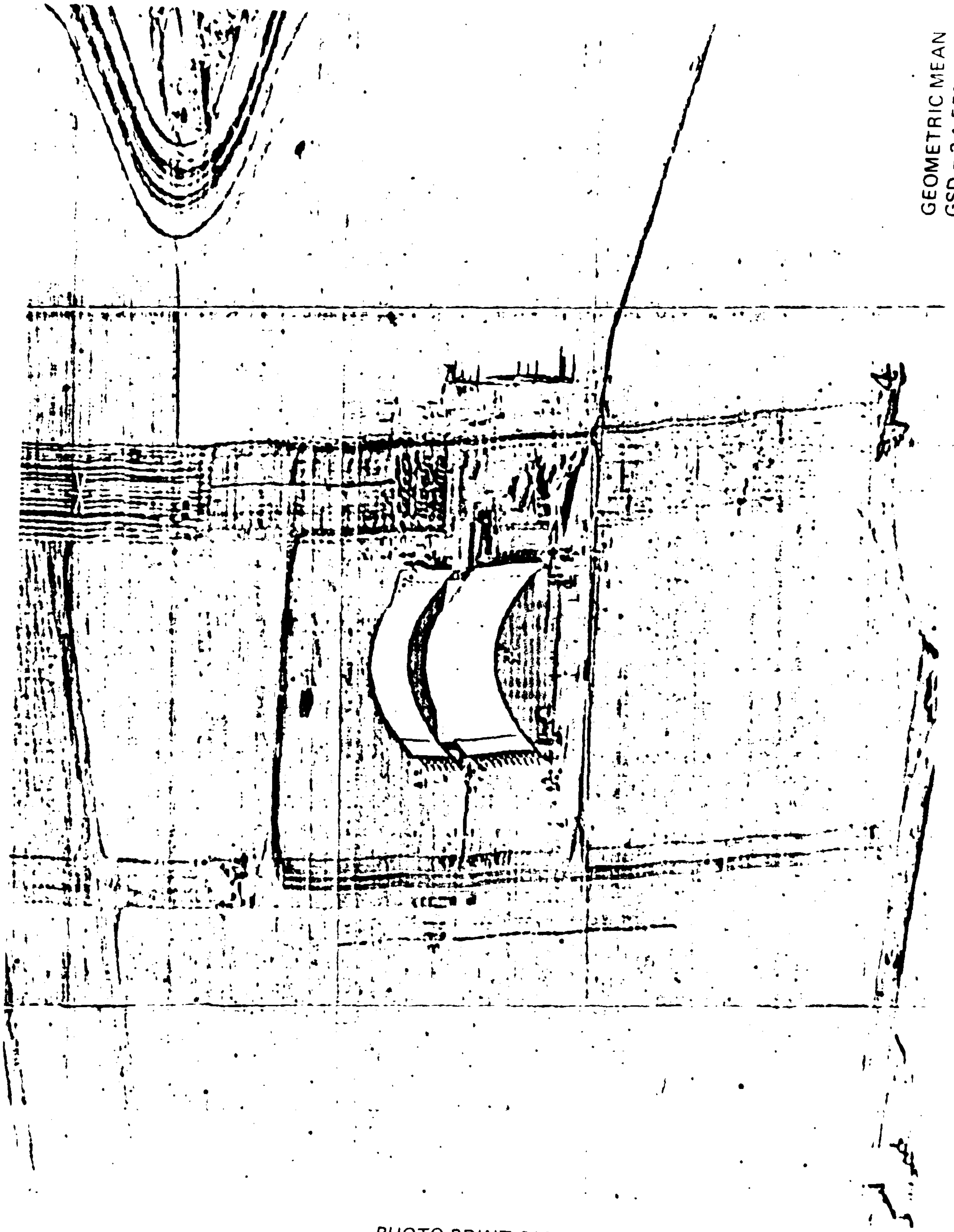
Thermal analysis of this configuration revealed acceptable thermal gradients across all optical surfaces. However, the glass surface closest to the sensor was still too cold, which would have caused convection currents in the scan head. This surface temperature could be raised by reducing the conductivity between it and the outside air stream. Conductivity would be reduced by lowering the

PHOTO PRINT C9



GEOMETRIC MEAN
GSD = 0.9 FEET

PHOTO PRINT C10



GEOMETRIC MEAN
GSD = 3.1 FEET

PHOTO PRINT C11

C4. LOREORS FLIGHT TEST IMAGERY FROM FLIGHTS 20,21,&22

(U) During the last quarter of the flight test program most of the stabilization problems had been cured. There was never a serious problem with the image acquisition system, since the first flight high resolution imagery was obtainable. The lack of stabilization during imaging acquisition caused the ultimate reproduction of the imagery to appear degraded, however, a close inspection was fairly good.

~~(C)~~ Samples of the imagery from the last few flights have been included as prints C12 thru C14. Print C12 is an enlargement from a scan taken at 20000 ft. at an imaging range of 9 miles with a contrast range of 1.05 to 1. The resolution of this image is demonstrated by the school in the foreground. (The building is identified as a school by the swing set between the buildings.) Details such as the fence posts around the building, stop signs and parking meters attest to the resolution of imagery. Print C13 slant range is 11 NM and Print C14 slant range is 36 NM.

PHOTO PRINT C12

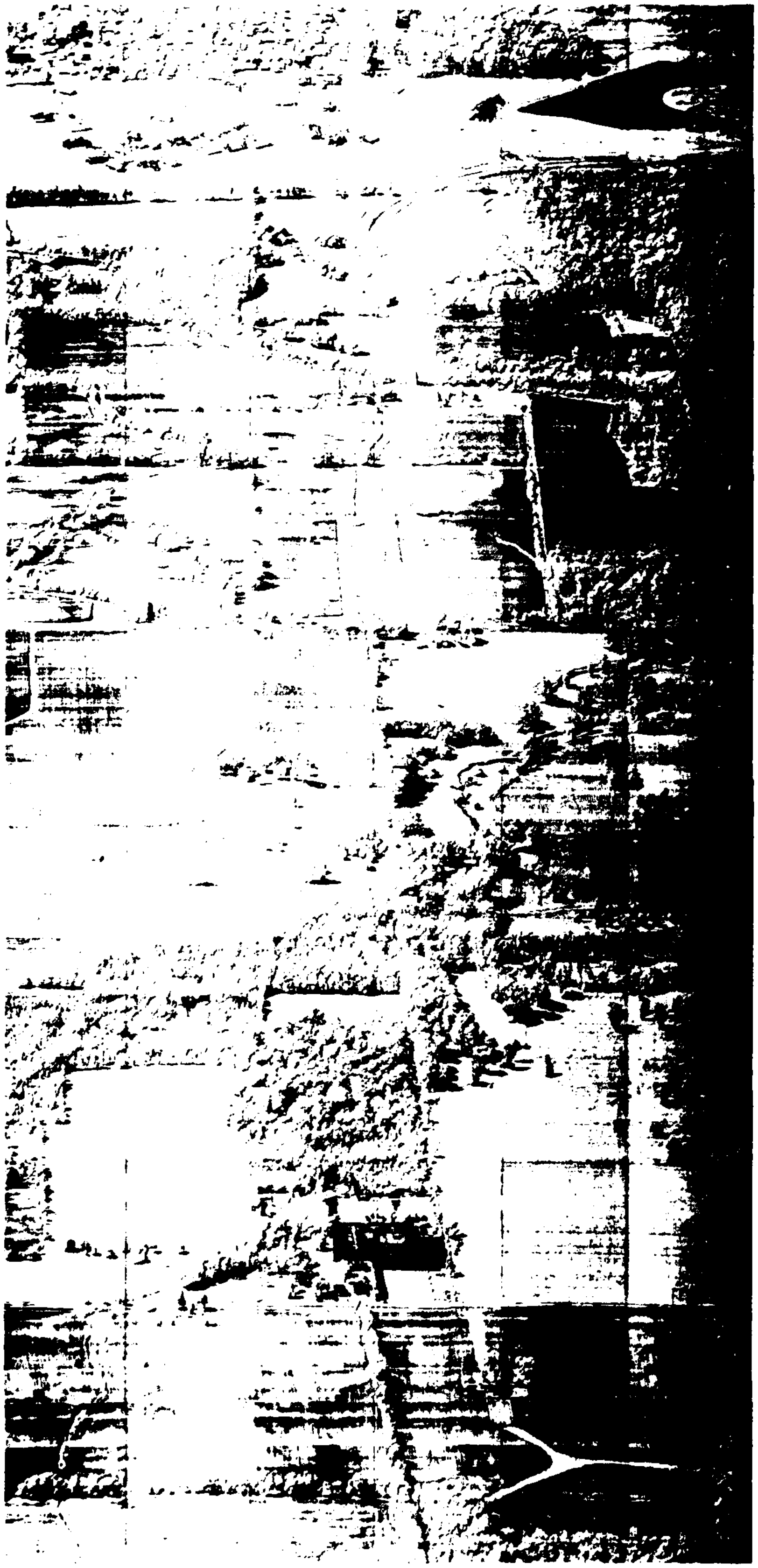


PHOTO PRINT C13

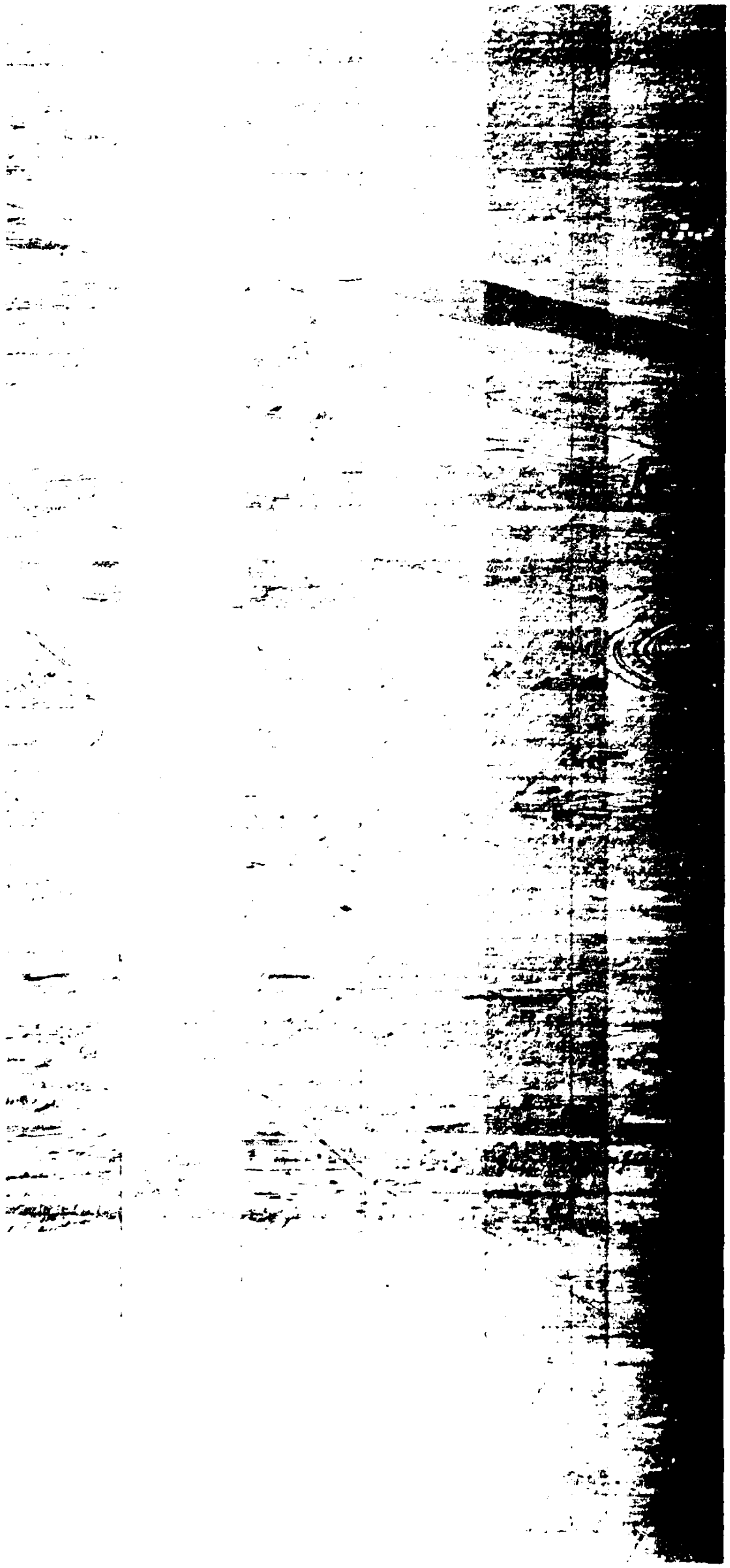


PHOTO PRINT C14

APPENDIX D

GLOSSARY

LOREORS	Long Range Electro-Optical Reconnaissance System
E/O	Electro-Optical
CCD	Charge Coupled Device
TDI	Time Delay and Integration
S/N	Signal to Noise
FISD	Fairchild Imaging Systems Division
TV	Television
VTR	Video Tape Recorder
GFE	Government Furnished Equipment
LBR	Laser Beam Recorder
INS	Inertial Navigation System
CDR	Critical Design Review
IR&D	Internal Research and Development
PEL	Photosensitive Element
PIXEL	Pixture Element
DMA	Direct Memory Access
RTE	Real Time Executive
STP	Standard Temperature and Pressure
FIFO	First in First Out

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